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Agricultural, Food, and Water Nanotechnologies for the Poor

Opportunities, Constraints, and Role of the Consultative Group on International Agricultural Research

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Contents

List of Tables

List of Figures

ABSTRACT

There are a number of potential opportunities associated with agricultural, food, and water nanotechnology for the poor, but to achieve such opportunities a number of challenges need to be overcome. This paper first provides a rapid assessment of key technologies that could have a large impact on the poor via increased agricultural productivity, improved food and water safety, and nutrition. Second, it reviews some of the main challenges to their deployment and adoption by the poor. It concludes with a discussion of the potential role of the CGIAR in facilitating the poor's access to beneficial nanotechnologies.

Keywords: nanotechnology, research and development priorities, developing countries, CGIAR

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1. INTRODUCTION

About three-fourths of the poor in developing countries, including the poorest of the poor, live in rural areas, and most depend on agriculture for their livelihood (Ahmed et al. 2007; World Bank 2008). In this context, agriculture is widely viewed as a strategic area to reduce poverty and foster development. While agricultural and rural development may not tackle all poverty, it is a necessary means to reduce poverty, especially in developing countries. Agricultural development is also a key to reducing hunger and malnutrition in a world where an estimated one billion people are malnourished or food insecure. Links between persistent poverty and hunger are well known (for example, see Ahmed et al. 2007). While insufficient income most often leads to lower access to safe food and water, hunger and malnutrition reduce the physical and intellectual capacity of individuals, thereby increasing their likelihood to become or remain poor (Hoddinott et al. 2008).

A comprehensive review of past research on agricultural development has identified effective pathways and tools to increase food security and reduce poverty (World Bank 2008). Among those, increasing the competitiveness of agriculture producers and improving market access are direct means to increase the welfare of the poor. Both producing more and connecting farmers to markets can help the rural poor increase their income and their access to food and other services. These two factors can also contribute to increasing the resilience of the poor to external shocks that can have a significant and lasting effect on their livelihoods.

Food safety is also a fundamental component of food security that can have an immediate impact on the poor. According to the Rome declaration at the 1996 World Food Summit, "Food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life" (FAO 1996). Food safety and security are intrinsically linked with the safety and availability of water, a crucial input into production of food, both pre- and postharvest. Moreover, food and water safety affect the livelihoods of poor producers and consumers through health and market access.

As shown in the past, science and technology have a significant and necessary role to play in these areas (Spielman and Pandya-Lorch 2009). Whether by increasing productivity of fields, improving food and water quality, or helping to improve market access, new technologies can enable faster advancements in these directions and provide high returns to investments. Although there are debates on the tradeoff between investing in the development and diffusion of well-known past technologies versus that of new and potentially revolutionary technologies, several examples show that both of these strategies may be beneficial and are sometimes complementary. In some cases, technological advances driven by demand, like mobile phones, can have an enormous impact and even replace previous technologies (such as land-based telephones) before their complete diffusion. In other cases, like agricultural biotechnology, continued investment in existing practices (conventional breeding techniques) is necessary to move forward and have an impact on the ground. The question for public authorities is how to approach the prioritization of research and development efforts with limited budgets and scientific capacity.

Advances in nanoscale sciences may present a new opportunity to help address these issues and improve the livelihood of the poor (Hillie et al. 2006; Larkins et al. 2008; Nature Nanotechnology 2007). *Nanotechnology* is research and development that involves measuring and manipulating matter at the atomic, molecular, and supramolecular levels at scales measured in approximately 1 to 100 nanometer (nm) in at least one dimension (NNI 2007). At this scale, the physical, chemical, and biological properties of materials may be fundamentally different from their corresponding bulk materials. Materials at such small scales often exhibit different electrical, magnetic, and optical properties than their bulk material counterparts, leading to the development of potentially revolutionary technologies in all industries; but they may also create potential new risks. Because nanoscale science and engineering are still at their early stages, it is difficult to gauge the future importance of nanotech applications; but most observers in the nanotechnology field believe that they are bound to have a gigantic effect, altering technologies used in all types of industries, provided their risks can be managed.

If most nanotech investment and technologies are in other industries, then investments in agricultural and food nanotechnologies are increasingly important (Kuzma and VerHage 2006). Although no precise figure is available, a largely cited 2006 consultant report estimated that agricultural and food nanotechnologies would represent about $20 billion of investment in 2010 (Helmut Kaiser 2006). The reported advantages of nanotech applications in food range from improved food quality and safety to reduced agricultural inputs and improved processing and nutrition (Doyle 2006; Garber 2006; Miller 2010; Nord 2009; Yada 2009). Current applications are mostly coming from food manufacturing industries in developed countries and may not all have direct impact on agricultural development. Packaging materials for produce and processed products appear to occupy a large share of currently available applications.

Still, research advancements provide glimpses of potential applications with clear impact on agricultural, food, and water safety that could have a significant impact on rural populations in developing countries (Anane-Fenin 2008; Claassens and Motuku 2006; Hillie et al. 2006; Larkins et al. 2008; Waruingi and Njoroge 2008). A consultation of international experts in nanotechnology and development in 2005 identified applications to enhance agricultural productivity and food processing and storage among the 10 top areas where nanotechnology has a high potential for development (Salamanca-Buentello et al. 2005). Several developing countries already believe in the potential of nanotechnology. For instance, India has included agricultural productivity as one of its main focuses for public research in nanotechnology (Sreelata 2008); Iran launched a 35-lab research program on nanofood applications in 2005 (Joseph and Morrison 2006).

At the same time, agricultural and food nanotechnologies, and especially those that could lead to reduced poverty or food insecurity, are bound to face many challenges before being commercialized and used by rural poor. As with other new technologies (Ludlow, Bowman, and Hodge 2007), all steps in the process may need to overcome constraints—from investment and research and development to regulatory approval, commercial release, distribution, access, availability, adoption, and proper use by users. But there are also specific issues with nanotechnology (Ludlow, Bowman, and Hodge 2007), such as the involvement of public research, the issue of intellectual property rights (IPRs), the management of safety and environmental risks in the presence of wide uncertainties, and the indirect effects on exports and foreign market access that could be positive or negative. Whether nanotechnologies succeed in helping the poor will largely depend on whether public research institutions, technology developers, national governments, and international donors are able to address these multiple challenges in the coming years.

In this paper, we analyze the potential opportunities and challenges of using nanotech applications in food and agriculture in developing countries. We use secondary data from the literature on agriculture and food nanotechnology and combine it with policy lessons from our own research on past and current agricultural, food, and water technology deployment in developing countries. Several papers have reviewed agricultural and food nanotechnologies in a developed-country context (Doyle 2006; Joseph and Morrison 2006; Kuzma 2010; Scott and Chen 2003), and others have analyzed the potential of all applications in developing economies (Foladori and Invernizzi 2008; MacLurcan 2005; Romig et al. 2007); but only a few publications have looked at agricultural and food nanotech in a developing-country context (Hillie et al. 2006; Meridian Institute 2007). We complement these efforts by analyzing the potential benefits of selected new and upcoming technologies and by assessing the potential policy and economic barriers to their adoption and use by the poor.

In so doing, we also discuss in general the actors involved in basic and applied research, in increasing agricultural productivity, in improving food nutrition, and in food and water safety research—key areas in nanotechnology that the poor can benefit from. We conclude with a discussion of the future potential role of the Consultative Group on International Agricultural Research (CGIAR) in exploiting opportunities and confronting challenges, at a time when the CGIAR is reforming its objectives, organization, and management. We hope that this paper can serve as a first step for discussion on the future strategies of the CGIAR, in partnership with National Agricultural Research Systems (NARS) and other efforts, toward the use of effective new technologies for the poor.

The following section reviews several applications of nanotechnologies with great potential benefits for the poor. Section 3 provides an overview of the policy challenges in the road to development and beneficial use of nanotechnology, and Section 4 discusses the potential future role of the CGIAR. We close the paper with some general policy conclusions and a set of exploratory research questions that will need to be addressed.

2. POTENTIAL BENEFITS OF NANOTECHNOLOGY FOR THE POOR

While we are still at the early stage of the nano revolution, current and upcoming nanotechnology applications in agriculture, food, and water already present great potential for the poor. In this section, we focus on these technologies, analyzing their potential benefits (risk mitigation, and so on) and why they have a high likelihood of increasing the benefits for the poor. Currently, in developing countries, few nanotechnology projects specifically target the needs of the poor (OECD and Allianz 2008). Nanotechnology has been identified as a scale-neutral modern technology—applicable to both large-scale commercial agriculturists and small-scale, resource-poor farmers (Lal 2007).

Several applications of nanotechnology are of interest to agriculture, although even in developed countries, nanotechnology is not currently in widespread use in the agricultural sector. Applications of nanotechnology currently noted to be in the food production chain include nanosensors and nanoagricultural chemicals (Bouwmeester et al. 2009). Nanoparticles for soil cleaning and nanopore filters were also reported to be in the food production chain (Bouwmeester et al. 2009). In the food production and processing phase of the food production chain, nanoceramic devices and nanoparticles (mostly silver nanoparticles) are reported to be in use (Bouwmeester et al. 2009). Over the next 5 to 10 years, an increasing number of nanotechnology applications are expected in developed countries for food and agricultural uses (USDA 2003). These applications include nanosensors, nano delivery systems, nanocoatings and films, nanoparticles, and quantum dots (Scott 2005; FAO-WHO 2009). Nanosensors are capable of detecting very small amounts of chemical contaminants, viruses, and bacteria in food, water, and environmental media (Scott 2005). Nano delivery systems can precisely deliver drugs or nutrients to the site within an organism where they are needed at the time they are needed and have the potential to minimize the use of the materials they deliver.

Of particular importance to developing countries are the nanotechnology applications addressing low use efficiency of inputs (such as nutrients, irrigation water, and pesticides) and stress of drought and high soil temperature (Lal 2007). Nanoscale agrichemical formulations increase the use efficiency and decrease losses into the environment (Lal 2007). More efficient nutrient delivery can be expected to result in increased yields (Joseph and Morrison, 2006). Nanoporous materials capable of storing water and slowly releasing it during times of drought can also be expected to increase yields. Applications of nanotechnology to reduce the effects of aflatoxin will increase the weight of food animals, resulting in more usable meat (Shi et al. 2006).

Five years ago, Salamanca-Buentello et al. (2005) conducted an expert elicitation of 63 international experts in nanotechnology to develop a list of the 10 most promising nanotechnology applications likely to benefit the poor in developing countries and to rank these applications in order of their likely benefits. One of the criteria for selecting a nanotechnology for inclusion in the list was its feasibility and the likelihood that it would be developed and deployed within the next 10 years. The selected experts were from both developing countries (60%) and developed countries (40%). Though the top application was for energy storage, production, and conversion of the top 10 applications, agricultural production ranked 2nd, water treatment and remediation ranked 3rd, food processing and storage ranked 6th, and vector and pest detection and control ranked 10th. These applications were linked by the authors of the study with the UN Millennium Development Goals to (1) eradicate extreme poverty and hunger; (2) reduce child mortality; (3) improve maternal health; (4) combat HIV/AIDS, malaria, and other diseases; and (5) ensure environmental sustainability (Salamanca-Buentello et al. 2005).

The National Research Council (NRC) of the National Academy of Sciences convened a panel to identify emerging technologies to benefit farmers in sub-Sahara Africa and South Asia in 2008 (NRC 2008). Nanotechnology-based soil applications to increase water retention and provide slow release of water and nutrients were identified as a technology to be given high priority for further exploration. Nanotechnology is predicted to have an impact on increasing agricultural production to the extent that it can improve soil quality. The committee identified the poor quality of soil in Africa and Asia as a limiting factor to agricultural production. The committee also identified the advances in energy storage and capture from the use of nanomaterials in solar photovoltaic cells and supercapacitors to provide benefits to developing countries' agricultural production in the future, although such operations are not currently feasible. The use of small nanofiltration devices holds promise for reclaiming wastewater for use in irrigation in periurban agriculture. Such filtration devices are rapidly emerging and may be feasible for small-scale production. Others have identified nanotechnology applications expected over the next five years in agriculture to focus on plant growth and insect protection (Niosi and Reid 2007).

In the following sections, we review applications that have good potential in agricultural production, food safety and nutrition, and water safety. While this list of applications is not exhaustive, it identifies some of the most promising technologies in each of these areas in which development or commercialization is anticipated in the near future.

Agricultural Production

Nanotechnology-aided applications have the potential to change agricultural production by allowing better management and conservation of inputs to plant and animal production. Currently, such nanotechnologies have been reported to be in use in the form of nanosensors, nanopesticides (Bouwmeester et al. 2009; Mukal et al 2009), nanoscale adjuvants for pesticides (Bio-Based 2010), smart delivery systems for nanoscale pesticides and fertilizers (Mukal et al 2009), feed additives (Shi et al. 2006; Spriull 2006) in veterinary medicines (Ochoa et al. 2007), in aquaculture (Kumar et al. 2008) as biosensors (FSA 2008), plant growth regulators (Choy et al. 2006) and the use of plants to synthesize nanoparticles (Gardea-Torresdey et al. 2002, 2003).

Salamanca-Buentello et al. (2005) include several nanotechnology applications for agricultural production that the experts in their survey predicted to be available for developing countries within the next 10 years. These included nanoporous zeolites for slow release and efficient dosage of water and fertilizers for plants; nanoporous zeolites for slow release of nutrients and drugs for livestock; nanocapsules for herbicide delivery; nanosensors for soil quality and for plant health monitoring; nanosensors for pest detection; nanomagnets for removal of soil contaminants; and nanoparticles for new pesticides, insecticides, and insect repellents (Table 1; Salamanca-Buentello et al. 2005). Some of these applications are discussed separately below.

Nanoherbicides

Several pesticide manufacturers are developing pesticides encapsulated in nanoparticles (OECD and Allianz 2008). These pesticides may be time released or released upon the occurrence of an environmental trigger (for example, temperature, humidity, light). It is unclear whether these pesticide products will be commercially available in the short term.

Adjuvants for herbicide applications are currently available that claim to include nanomaterials. One nanosurfactant based on soybean micelles claims to make glyphosate-resistant crops susceptible to glyphosate when it is applied with the nanotechnology-derived surfactant (Bio-Based 2010). The regulatory structure in developed countries is driving development of nanoscale pesticides and herbicides in the direction of nanoscale adjuvants rather than nanoscale-active ingredients (Observatory NANO 2010). Whether the nanoapplication is due to a nanosized active ingredient or the creation of a nanosized formulation through the use of an adjuvant, the benefits of nanoapplication are similar: Less herbicide is required to achieve the weed reduction effects desired. If the active ingredient is combined with a smart delivery system, herbicide will be applied only when necessary according to the conditions present in the field. Soils infested with weeds and weed seeds are likely to produce lower agricultural yields than soils where weeds are controlled. Improvements in the efficacy of herbicides through the use of nanotechnology could result in greater production of crops and less injury to agricultural workers who must physically remove weeds if herbicides are not used.

Nanofertilizers

Nanofertilizers have the opportunity to profoundly impact energy, the economy, and the environment by reducing nitrogen loss due to leaching, emissions, and long-term incorporation by soil microorganisms (DeRosa et al. 2010). Currently, the nitrogen use efficiency of plants is low due to the loss of between 50% and 70% of the nitrogen supplied in conventional fertilizers. New nutrient delivery systems that exploit the porous nanoscale parts of plants could reduce nitrogen loss.

Fertilizers encapsulated in nanoparticles will increase the uptake of nutrients. In the next generation of nanofertilizers, the release of the fertilizer can be triggered by an environmental condition or simply be time released. Slow-, controlled-release fertilizers have the potential to increase the efficiency of nutrient uptake. Nanofertilizers that utilize natural materials for coating and cementing granules of soluble fertilizer have the advantage of being less expensive to produce than those fertilizers that rely upon manufactured coating materials (Lui et al. 2006). Slow-, controlled-release fertilizers may also improve soil by decreasing toxic effects associated with overapplication of fertilizer. Zeolites have been used as fertilizer delivery mechanisms.

Nanosensors

Sensors are devices that respond to physical, chemical, or biological conditions and convert that response into a signal or output in a useful form for a human user. *Nanosensors* use nanoscale devices to accomplish this task (NNCO 2009). They allow the detection of contaminants; pests; nutrient content; and plant stress due to drought, temperature, insect or pathogen pressure, or lack of nutrients. The current state-of-the-art nanosensors are not in widespread commercial use, even in developed countries; but considering the speed at which the field of nanotechnology is developing, it is likely that nanosensors will become widely available in the near future. Nanosensors have the potential to allow farmers to utilize inputs more efficiently by indicating the nutrient or water status of crop plants over fine spatial and temporal scales, allowing the farmer to apply nutrients, water, or crop protection (insecticide, fungicide, or herbicide) only where necessary.

Nanofeed Additives

The U.S. Department of Agriculture and Clemson University have developed a chicken feed containing bioactive polystyrene nanoparticles that bind with harmful bacteria to reduce food-borne pathogens (OECD 2010). Nanoclays (for example, modified montmorillonite nanocomposite) ameliorate the deleterious effects of aflatoxin on poultry (Shi et al. 2006).

Smart Drug Delivery Systems

Smart delivery systems are nanoscale devices that have the capability to detect and treat an animal infection or nutrient deficiency and can be designed to provide time-controlled release of drugs or nutrients (Scott 2005). This application is apparently not currently in widespread or commercial use and will require substantial effort to integrate nanotechnology, biotechnology, and information technology with geographic information systems (Kuzma 2010). Some estimate that while the building blocks exist to design smart drug delivery systems, it may be decades before they are in commercial use (Scott 2007).

Nanocoatings

Poultry houses in North America use bactericidal coatings to reduce the concentration of food-borne pathogens in contact with the poultry during production. Green Earth Nano Science, Inc., a Canadian company, has developed a self-sanitizing photocatalyst coating for use in poultry houses (GENS 2009). This coating incorporates nano titanium dioxide (TiO_2). The unique photocatalytic properties of the nano TiO_2 are activated when the coating is exposed to natural or ultraviolet light. In the presence of light and humidity, the TiO_2 oxidizes and destroys bacteria. The coating has been demonstrated to reduce bacterial growth. Once coated, the surface remains self-sanitizing as long as there is enough light to activate the photocatalytic effect. The coating is approved by the Canadian Food Inspection Agency. In Denmark, the Chicken and Hen Infection Program is experimenting with nanocoatings for self-cleaning and disinfection (Clemants 2009). The smooth surface at the nanoscale makes cleaning and disinfection more effective. Finally, Danish researchers are also investigating coatings incorporating nanosilver, which does not require ultraviolet light for activation. The ions from nanosilver prevent the development of biofilms (Clemants 2009).

Zeolites for Water Retention

Zeolites are naturally occurring crystalline aluminum silicates that have flexible internal structures, allowing for the exchange of ions and reversible dehydration. In addition to naturally occurring zeolites, these crystals can also be synthesized. Zeolites can improve the water retention of sandy soils and improve porosity in clay soils. The NRC (2008) identified soil quality as the number one issue for improving crop yields in sub-Saharan Africa and southern Asia. Improving water-retention capacity of soils could result in increased crop production in areas prone to drought.

Food Safety and Nutrition

Spoilage of food and the incorporation of toxic substances are problems throughout the world, but perhaps especially detrimental to developing countries with poor cold-storage facilities. Salamanca-Buentello et al. (2005) identify several nanotechnology applications for food safety and nutrition that the experts in their survey predicted to be available for developing countries within the next 10 years. These include nanocomposites for plastic film coatings used in food packaging; antimicrobial nanoemulsions for applications in decontamination of food equipment, packaging, or food; nanotechnology-based antigen-detecting biosensors for identifying pathogen contamination; nanosensors for pest detection; and nanoparticles for new pesticides, insecticides, and insect repellents.

Enhanced Barriers to Microbial Contamination or Spoilage (Nanoclays, Nanofilms, Embedded Nanoparticles)

Barriers can reduce opportunity for microbial contamination by preventing bacterial access to food or preventing conditions amenable to bacterial growth from occurring. *Nanocomposites*, plastics that contain nanomaterials, can provide effective barriers to gas extrusion. Nanoclays have been used to reduce carbon dioxide and oxygen permeability in plastic beverage containers. Nanofilms also have been used to restrict oxygen contact with food.

Detection of Food-borne Pathogens or Spoilage Organisms (Nanosensors in Packaging or Processing)

New biosensors are being developed at a rapid pace. While many of these biosensors are still in the research and development stage, it will not be long before they are deployed in commercial applications (for example, low-cost test strips). Nanobiosensors are rapidly being developed to detect a wide range of pathogens in a variety of media.

Nano-based methods of detecting harmful pathogens are being developed for several pathogens. A nanobiosensor that detects o-nitrophenol produced by *Escherichia coli* could be deployed to identify the presence of hemorrhagic *E. coli* and prevent the consumption of contaminated foods (Majid et al. 2008).

Nano-based Veterinary Treatments (Nanoclays to Decrease Aflatoxin Effects in Food Animals, Nano Veterinary Drugs)

An aflatoxin-binding nanoadditive for animal feed that is derived from modified montmorillonite (nanoclay) is currently in the research and development stage (Ying-hua et al. 2005). Modified montmorillonite nanocomposite has been used to deactivate aflatoxin (Shi et al. 2006) and deoxynivalenol and zealarone mycotoxins (EFSA 2009). Zeolitic minerals and clays have generally been shown to bind to aflatoxin and greatly reduce its uptake and bioavailability (Binder 2007).

Nanoparticles that adhere to *E. coli* are designed to be administered through feed to remove food-borne pathogens in the gastrointestinal tracts of livestock (Kuzma et al. 2008). A biofunctionalized nanoparticle with an affinity for *Campylobacter* has been tested as a feed additive to reduce pathogen levels in poultry (Spruill 2006).

Detection of Pesticides, Heavy Metals, or Other Chemical Contaminants

Biosensors provide high performance capabilities for use in detecting contaminants in food or environmental media. They offer high specificity and sensitivity, rapid response, user-friendly operation, and compact size at a low cost. (Amine et al. 2006). Several nano-based biosensors based on direct enzyme inhibition have been developed to detect contaminants (Amine et al. 2006). While the direct enzyme inhibition sensors currently lack the analytical ability to discriminate between multiple toxic substances in a sample (such as simultaneous presence of heavy metal and pesticide), they may prove useful as a screening tool to determine when a sample contains one or more contaminants (Amine et al. 2006). These methods are amenable to deployment in single-use test strips (making them useful to those in the field).

Biosensors using nanotechnology may also require sophisticated equipment, making these techniques less attractive for use in developing countries. An example of this type of nanobiosensor is a gold nanoparticle-based sensor that detects crystal violet or malachite green—prohibited dyes used to reduce fungal and parasitic infection—at concentrations as low as 2 ppb in seafood (He et al. 2008). The nanosensor uses a spectrometric test, which may be too costly for developing countries. A technique that requires less use of specialized equipment is voltammetric detection using a nanocomposite film of zirconia-gold ZrO_2/Au nanoparticles (Wang and Li 2008). Such a technique was used to detect parathion residues at a detection limit of 3 ng/mL. This technique is still dependent on the use of standard laboratory equipment and electricity. According to Hu et al. (2010), detection of multiple residues of organophosphorus pesticides has been accomplished using a nanomagnetic particle in an enzyme-linked immunosorbent assay (ELISA) test. The authors suggest that ELISA is more cost-effective than analytic tests requiring expensive laboratory equipment and that it does not require the same high levels of skill as tests using analytical chemistry.

Water Safety

Water will become a limited resource worldwide by the end of this century. Improvement in drinking water is of significant benefit to human health in developing areas, especially when improvement is made close to the point of use—at the household (World Health Organization 2008).

Improving the drinking water quality in developing countries will yield benefits. Several nanotechnology applications may help to improve drinking water. These applications fall into three broad categories: improved filtration mechanisms (carbon nanotube membranes), improved detoxification of harmful pollutants (zero-valent iron nanoparticles, and so on), and pollution-prevention techniques (nanopesticides designed for reduced transport from site of application).

Salamanca-Buentello et al. (2005) identify several nanotechnology applications for drinking water safety that the experts in their survey predicted to be available for developing countries within the next 10 years. These include nanomembranes for water purification, desalination, and detoxification; nanosensors for the detection of contaminants and pathogens; nanoporous zeolites, nanoporous polymers, and attapulgite clays for water purification; magnetic nanoparticles for water treatment and remediation; and titanium dioxide nanoparticles for the catalytic degradation of water pollutants (Table 1).

Filtration

The NRC report (2008) on emerging technologies that will benefit farmers in Africa and Asia lists several nanomaterials that are believed to be economical and effective for water purification. Nano-enabled water treatment techniques rely on membranes and filters made of carbon nanotubes, nanoporous ceramics, and magnetic nanoparticles rather than the use of chemicals and ultraviolet light used in conventional water treatment (Hillie and Hlophe 2007). Carbon nanotube filters can be used to remove impurities from drinking water. Scientists at Rensselaer Polytechnic Institute (Troy, New York) and the Banaras Hindu University (Varanasi, India) are collaborating in the design of a carbon nanotube filter to remove bacteria and viruses from water (UN 2006). A fused carbon nanotube mesh that can filter out water-borne pathogens, lead, uranium, and arsenic has been suggested as a useful nanotechnology by the NRC report. The NRC report also discusses the application of the NanoCeram filter, which uses a positively charged filter to trap negatively charged bacteria and viruses. This filtering device removes endotoxins, DNA, viruses, and micron-sized particles (Argonide 2005).

Magnetic Nanoparticles for Filtration

Using magnetic nanoparticles, magnetic separations are now possible at very low magnetic field gradients. Monodisperse magnetite (Fe_3O_4) nanocrystals have a strong and irreversible interaction with arsenic while retaining their magnetic properties (Yavuz et al. 2006). A simple handheld magnet can be used to remove the nanocrystals and the arsenic from water (Yavuz et al. 2006). Such a treatment could be used as a point-of-use water filtration process.

Removal or Detoxification of Harmful Pollutants

Arsenic removal by a synthetic clay nanomineral requires no expensive laboratory equipment (Gilman 2006). The water to be filtered is percolated through a column of hydrotalcite (synthetic clay mineral). Gilman (2006) suggests that this technology can be coupled with leaching through porous pots or filter candles, the technology available in many developing countries to filter organisms from drinking water. Zinc oxide nanoparticles can be used to remove arsenic using a point-of-source purification device (NRC 2008).

Remediation or Detoxification

Nanoscale zero-valent iron (nZVI) is the most widely used of the set of nanomaterials that could be deployed to remediate pollutants in soil or groundwater. Other nanomaterials that could be used in remediation include nanoscale zeolites, metal oxides, carbon nanotubes and fibers, enzymes, various noble metals (mainly as bimetallic nanoparticles), and titanium dioxide (Karn et al. 2009).

Pollution Prevention Techniques

Nanoparticle filters can be used to remove organic particles and pesticides (for example dichlorodiphenyltrichloroethane [DDT], endosulfan, malathion, and chlorpyrifos) from water (NRC 2008). A variety of nanoparticle filters have been used in remediation of waste sites in developed countries (Karn, Kuiken, and Otto 2009).

3. KEY CHALLENGES AHEAD

Important constraints exist in the use of promising nanotechnology applications for the poor, including internal (in-country) constraints to development and adoption as well as external factors that could also have a direct or indirect effect on the future use of nanotechnologies in agriculture and food in developing countries. In particular, we focus on three major constraints: research and development investments, barriers to access and adoption, and the presence and governance of risks associated with nanotechnologies. In each case, we provide a rapid situation analysis and review the policy implications. Naturally, while the above-listed technologies will face these challenges, this section also applies to other nanotechnologies in agriculture and food.

Research and Development Investment for the Poor

A necessary condition to the development of adapted and appropriate technologies is the presence of sufficient research and development investments, whether in the public or private sector. Lack of support for nanotechnology science and applications in developing countries could force these countries to either abandon nanotechnology options or import (transfer) existing technologies from other countries, which may need to be adapted to their needs. If the technologies cannot be transferred directly and there is no capacity to adapt it to the poor's needs, then the poor may be excluded from the benefits of nanotechnology.

Currently, large emerging economies have heavily invested in nanotechnology, looking at it as an opportunity of leapfrogging (Romig et al. 2007), while smaller developing countries have stayed behind (Niosi and Reid 2007). In particular, Brazil, China, and India have invested in nanotechnology, with the goal of catching up with other countries (Niosi and Reid 2007). Each of these countries has followed a specific strategy: China has been putting significant effort into infrastructure and patents (Nemets 2004); India's efforts were focused on infrastructure, and Brazil's on basic research not translated into industrial applications. While these countries' investments are cross-sectoral, Brazil and India did invest in specific agricultural or food programs (Sreelata 2008; Meridian Institute 2007).

In Latin America, where funding has been documented, apart from Brazil, Argentina leads the region, with Chile, Colombia, and Mexico also developing capacity (Foladori and Invernizzi 2008). The driving force for investment in these countries is competitiveness; nanotech investment is a step in the race to catch up with developed nations and invest in future technologies. Foladori and Invernizzi (2008) note that most nanotechnology investments are in the public sector alone and that there is currently less emphasis on some of the principles, such as societal issues, risk assessment, and communication, that are likely to fashion the future of consumer products made from nanotechnologies.

Other developing countries have also invested in nanotech. Costa Rica, Egypt, Georgia, Iran, Malaysia, the Philippines, South Africa, Thailand, and Vietnam have set up national funding programs (MacLurcan 2005). Botswana, Cuba, Indonesia, Jordan, Kazakhstan, Pakistan, Uzbekistan, and Venezuela reportedly have local research teams involved in nanotech (MacLurcan 2005). But these efforts are much smaller than observed in the "big three" involved in nanotechnology research namely—Brazil, China, and India; and only Iran (Joseph and Morrison 2006), Thailand (Liu 2009), and to a smaller extent Malaysia (Hashim, Nadia, and Salleh 2009) reportedly have a program focused on agriculture or food. Several others, like South Africa (Claassens and Motuku 2006; Department of Science and Technology 2005), include a specific focus on water quality.

Niosi and Reid (2007) suggest that smaller developing countries may be able to follow after the large ones (Brazil, China, India) in the future if they follow two strategies: (1) take advantage of the intersections between nanotechnologies and biotechnologies—for example, build on existing institutional and physical capacity—to lower the cost of entry; and (2) partner with bigger countries to take advantage of their advancements. But overall, Niosi and Reid (2007) do not believe that these smaller developing countries will have a major role to play in global competition in nanotechnology in the near future.

Whether in large or small countries, public support for new agricultural technologies always faces general constraints. First, finding support and commitment for long-term investment in expensive, potentially risky, or uncertain research is not common. Changes in governments and donor priorities tend to push research toward shorter rotating investments. Second, research in the public sector tends to be dissociated from a product development approach; while research institutions may be relatively good at developing and releasing basic technologies (seeds), they may not have the capacity, expertise, or will to push a new technology forward toward testing and commercial release (as observed in the case of agriculture biotechnology). Third, the necessity to bring researchers from different disciplines together with regulatory and deployment specialists can prove difficult in countries with specialized institutions.

In the private sector, the key issue is whether there is sufficient infrastructure, basic capital, and sufficient economic incentives to invest into nanotechnology in agriculture and food in countries. The uncertainties of investment and technologies make it trickier for domestic companies to invest into long-term research and development programs. Larger companies and multinationals may also see developing-country markets as unprofitable, and the difficulty to enforce intellectual property rights (see Section 3.2.1) may also play a role. Furthermore, many barriers observed in developed countries, such as the lack of access to capital and insufficient connections to universities in the United States (Bozeman, Hardin, and Link 2008), are likely to be even greater in developing nations.

Apart from funding, the lack of human capacity, especially—but not only—in the public sector, is necessarily going to be a major barrier to overcome particularly in less-developed countries. Nanotechnology can only be on the horizon if countries start to develop curricula, train scientists of different disciplines into nanoscale sciences, or both (Anane-Fenin 2008; Waruingi and Njoroge 2008). The "brain drain" remains one of the overarching issues for any technological capacity development; most bright students from less-developed countries who pursue university degrees in developed countries do not return to their home country. This situation may worsen in the case of nanotechnology, as the United States is considering offering permanent residency to individuals obtaining science or engineering degrees in nanoscale scientific fields in U.S universities (President's Council of Advisors on Science and Technology 2010). Other nations of Europe or Asia may follow suit with similar initiatives and try to retain scientists trained in the nanosciences.

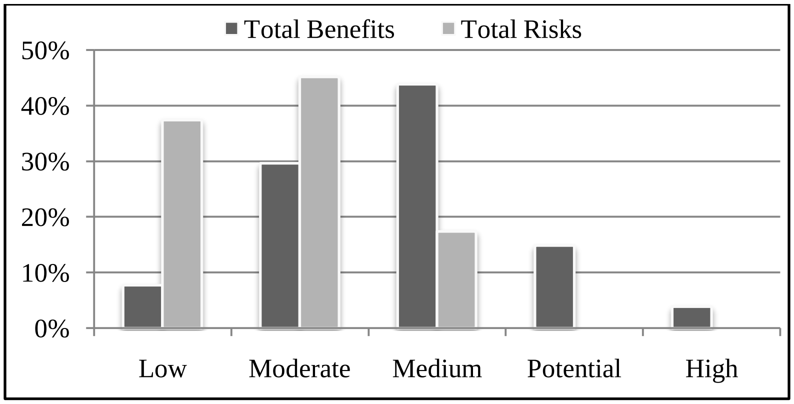
With limited resources, plus capacity and funding constraints, especially in agriculture, research prioritization should be done strategically. While investment in nanotechnology is necessary for any progress, it should not result in drastic cuts in existing research and development efforts. It is clear that most developing countries already have agricultural development strategies that still need to be reinforced (Sreelata 2008).

Currently, research prioritization in nanotech is being led in developed countries by a competitive call for grants, but the competitive grant approach is not adapted to the context in most developing countries. The competitive grant process requires applicants with sufficient capacity and interest in the nanotechnology area, which will not be found in some of the poorest countries with minimal or no high-level scientific research institutions working in nanotechnology. This means that in developing countries, the government and research agencies need to conduct a self-assessment of their own priorities for nanotechnology to disperse their funding or apply to external funding.

Still, it is useful to look at existing processes and learn from their experience. The U.S. National Nanotechnology Initiative (NNI) does allocate grants to research institutions in different fields of applications (President's Council of Advisors on Science and Technology 2010). Within the set of accepted grants, a number of research projects are focusing on agriculture and food applications. However, a rapid analysis of basic data from these projects shows that the prioritization may not be fully effective or at least consistent with economic efficiency objectives.

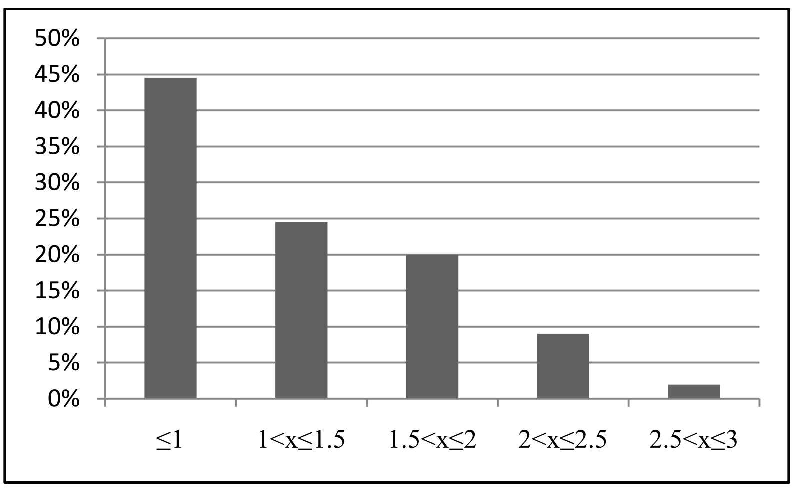
Kuzma and VerHage (2006) conducted a systematic listing of the 155 grant-awarded projects in this area. They then reviewed the objectives, methods, and budgets of these projects and evaluated them with qualitative indicators (each ranging from 1/low to 3/high) of potential health benefits, potential environmental benefits, potential environmental risks, and potential health risks, which are key factors in nanotechnologies. Interestingly, a simple analysis of their derived results[1] shows that the projects awarded are generally graded with medium benefits and moderate risks as shown in Figure 1. Furthermore, as shown in Figure 2, 45 percent of the awarded projects present benefits that do not exceed their potential risk indicators (benefit/risk ratios lower than 1), and only 2 percent have a maximum benefit/risk ratio.[2]

Figure 1. Distribution of NNI-awarded grants in agriculture and food by benefits and risks indicators



Source: Authors, derived from the database by Kuzma and VerHage (2006).

Figure 2. Distributions of NNI grant-awarded projects in agriculture and food by benefit/risk ratio



Source: Authors, derived from the database by Kuzma and VerHage (2006).

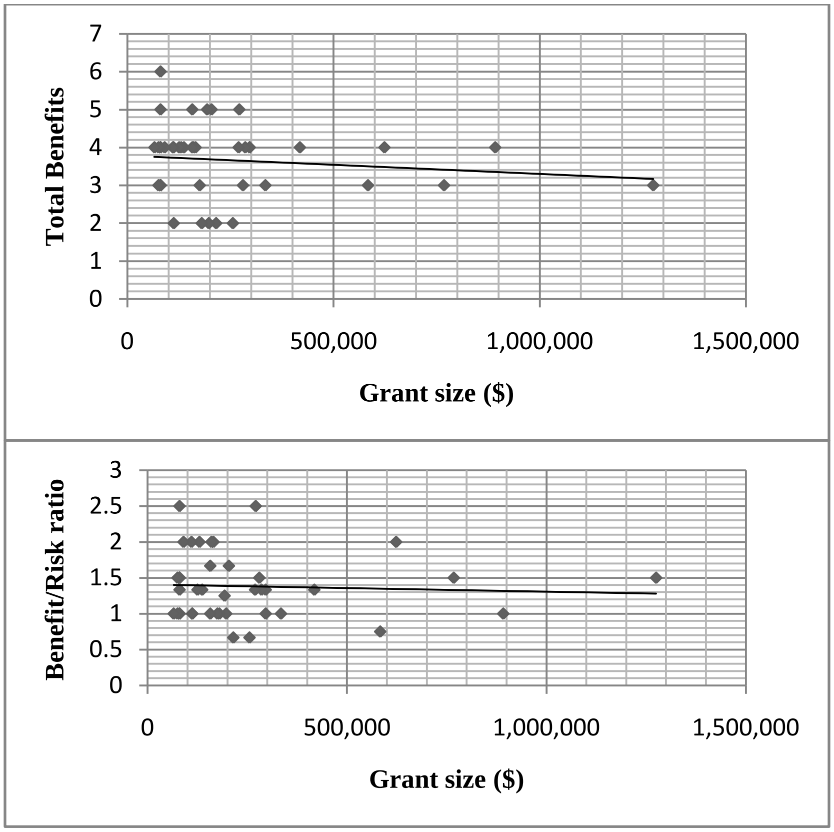
The decreasing pattern in Figure 2 indicates that the selection process is not effectively done to maximize the suggested benefit/risk ratios. This may be due to the fact that for the NNI, technological applications may not be as important as basic science, and naturally this may not be a goal of the NNI. Still, further analysis of projects with budget figures shows a nonpositive correlation between budget

[1] Total benefits are derived as the sum of the two benefit indicators (health and environment) and therefore range from 2 (low) to 6 (high), and similarly, total risks are computed as the sum of the two risk indicators and also range between 2 and 6.

[2] The benefit/risk ratios are simply compiled as the ratio of the total benefits and total risks as defined in the preceding footnote. These ratios therefore range between 1 and 3. A maximum benefit/risk ratio of 3 is only obtained for projects with high potential environmental and health benefits (3+3=6) and low health and environmental risk (1+1=2).

declines (or does not increase) and benefits and budget and benefit/risk ratios (Figure 3). Higher-funded projects present moderate benefits and relatively modest benefit/risk ratios, while projects with high potential benefits and low risks are only allocated smaller amounts.

Figure 3. Relationship between the budgets of NNI-awarded grants in agriculture and food, potential benefit indicators, and benefit/risk ratios



Source: Authors, derived from Kuzma and VerHage (2006).

Yet, for developing countries with more severe funding limitations, especially in agricultural research, the objective should arguably be to fund programs with applications that have the maximum benefit/risk ratios. It should be noted that benefits and risk will most often differ significantly more for poor people living in rural areas of developing countries than for consumers in developed countries, simply because their public priorities and livelihoods dramatically differ. For instance, accessible and usable technologies to help provide access to safe water and safe food would have dramatic effects in countries where food and water are not safe, resulting in sickness and increased mortality. In developed countries, the benefits will depend on whether these technologies can lower the cost of safe food and water and provide marginal increment in safety. Similarly, the presence of low risks with the use of nanotech may be sufficient for developed-country consumers to reject the technology, but it would have to be compared with the costs and risks of not having these technologies for poor people in developing countries.

Costs and Access to Nanotech Applications

Intellectual Property Rights, Innovation, and Technology Access

In private-sector development, economic incentives and capacity are significant factors to consider. Intellectual property rights (IPRs) play a critical role in the innovation process in a globalized world. The role of patents is increasingly important, especially in new technologies. With the progressive implementation of the Agreement on Trade Related Aspects of Intellectual Property Rights (TRIPS), one of the three pillars of the 1994 trade agreements under the World Trade Organization, an increasing number of developing countries are adopting IPRs. Companies' investments in research and development largely depend on future rents from users of technologies. Patents also provide incentive for research in all fields of science. But their use still generates significant criticism especially when related to the use of medical technologies for the poor in developing countries. Past economic research is relatively ambiguous regarding the effects of IPRs on investment, innovation, and economic development (Fink and Maskus 2005). Enforcing IPRs and more specifically, patents, while providing incentive for investment and innovation, can create barriers to entry and raise the cost of products for consumers. It may also contribute to a growing divide between developed and developing economies. Developing countries could establish incentives within their IPR regulatory systems to encourage development of applications that would mostly benefit developing countries. A system similar to that is used in the United States to encourage pharmaceutical companies to develop drugs to treat rare diseases (meaning Orphan Drug Act).

The number of international and U.S. patents is increasing on all types of nanotechnologies worldwide (MacLurcan 2005). A very large majority of these patents originate from nanotech-leading, developed countries like the United States, Western European nations, Japan, South Korea, and Australia (ETC Group 2005). In the developing world, so far, as noted above, only large, emerging economies (such as China) have developed patented technologies.

If sustained, this potentially unequal patent race may create a significant barrier to the use of promising technologies in the developing world. For instance, several key applications of nanoscience in animal production (for example, in animal breeding, tracking devices, and pathogen detection) could be difficult to access due to IPR protections (Kuzma 2010). Patents do by definition restrict access to technologies by outside users. In agriculture, this often translates into a situation of temporary monopolies with higher prices charged by the developing companies for any outside user. In many cases, these price increases are sufficient to make the technology prohibitive for poor farmers and users in developing countries. Some observers do believe that there will be a larger number of competitors in the nanotech field than in pharmaceutical or biotech sectors (Bowman and Gilligan 2007) and therefore that the pricing effect may not be as important as in these other sectors. But competition will clearly depend on the type of products developed, and given the lower number of actors involved in agriculture and food technologies, it may still be quite important.

Furthermore, the existence of "broad" patents covering essential methodological tools and technologies needed to handle or analyze nanomaterials may increase barriers to innovations within the developing world (ETC Group 2005). A country with enforced IPRs and the intention to develop research and development programs in applied nanoscale sciences may have to access basic tools and instruments that are already patented. Further, the users of the patented processes may only have access if they hold licenses—thus the intent to develop research and development programs on nanotechnology may not necessarily result in access to basic tools or instruments that are already patented if the patentholders are not also the researchers and developers. This will create additional costs and a barrier to entry for innovation.

On the other hand, the absence of any IPR protections could also be detrimental and result in the complete lack of access to potentially useful technologies to those that may benefit from them. In their report, Niosi and Reid (2007) suggest that small developing countries engage in early patenting to attract foreign direct investment and in creating clusters in technology to grow and catch up with the larger nations. This requires a proper IPRs system with patent registration, something that not all countries have.

In fact, technology transfer may be beneficial (Section 4). In the longer run, the use of any nanotech applications may be conditional on IPRs, and therefore avoiding the issue could be similar to a placing a moratorium. Lastly, private companies may also lack incentives to engage in these areas—and incentives from the government could help spur investment by private companies.

Still, an alternative to patents, which have been studied and used in the past—mostly but not only in health—is research prizes. These could help in advancing food and agricultural nanotechnology to developing countries and poor users. In particular, the use of research prizes can play a role in fostering innovation without forcing to have a right to pay (Masters 2003). The organizations offering prizes face practical issues such as that of prioritization (what issues are the most important) and time inconsistency.

Market segmentation strategies could also be used to reach poorer users, as done in several cases with drugs and improved seeds. While it has some challenges, it may also result in effective results. Various other schemes could be developed, depending on the technology, its targeted users, and developers. More research is needed to evaluate what approach would be best suited for broad-ranging nanotechnologies in agriculture, water, and food.

Patents themselves are not a prerequisite for obtaining the benefits of research. As with other types of investment, the ability of the private company to sustain sales of the technology is an important incentive for private research. The profitability of research can be undermined if other firms are able to copy a new technology and sell it to producers or if farmers can reproduce the technology themselves.[3] Poultry breeders have successfully protected their intellectual property investment in superior breeds by exploiting heterosis, or hybrid vigor (Bugos 1992). Hybrid vigor is the yield advantage obtained when two or more purebred lines are crossed in a breeding scheme. Although the offspring of this cross exhibit some superior yield performance, this yield advantage steadily declines if the offspring themselves are bred. Thus, by restricting access to the pure parent line stock (a form of trade secret), a breeder remains the sole supplier of the hybrid (Narrod and Fuglie 2000). Farmers need to repeatedly purchase new stock from the breeder to maintain high yields. Worldwide farmers rich and poor are obtaining the benefits of research developed by the private sector and transferred to developing countries in which the benefits were maintained via trade secrets.

Supply-and-Demand Constraints

Assuming that an adapted technology is developed and commercialized, the question remains whether it can be produced, distributed, and sold at an affordable price. As noted above, public-sector research institutions often lack expertise in commercialization strategies. Partnerships with private entities, associations, or other nongovernmental organizations are often necessary for production and dissemination of new technologies, especially to users in rural areas. The number of public–private partnerships in agricultural technologies is growing, including some that have shown successes; but these partnerships also face a number of institutional challenges (for example, Spielman, Cohen, and Zambrano 2006).

Ultimately, the access and affordability of technologies will determine whether they will be used by the poor. Many factors may create constraints to access (Sunding and Zilberman 2001), including limited market access by targeted users, lack of knowledge and information, and credit constraints. The final prices will depend on transaction costs and the capacity of the generating organization to distribute the products. Infrastructure, communication means, and financing constraints are not technology specific and can create prohibitive barriers to access. Market structure and market imperfections will also bear an effect on affordability.

Implementing regulations may also bear significant costs on developing nations. Not only will these countries have to form and manage expert teams, but the control and identification may bear high costs. In particular, nanoparticles and nano delivery systems are difficult to identify in food. While analytical methods to detect nanoparticles and nano delivery systems are being developed, it is likely that

[3] Those who copy can afford to sell the technology more cheaply than the original inventor does because they do not have to recoup the initial sunk costs of research and development.

a combination of analytic techniques will be required (Luykx et al. 2008). Such sophisticated tests are likely to be costly and out of reach for developing countries.

Last but not least, the demand of users for a new technology will drive whether or not the technology is successful and can sustain in the future. Adoption is conditional on users' willingness to pay for a new technology. In this process, knowledge and attitudes matter. All nanotechnologies will not require users to have the same type and level of knowledge, but the final users need at least to know that they exist, what their use is, and how they should be used. This basic information can be transmitted either directly by the seller or provider, or indirectly by extension agents or informed peers, such as family or community groups. Naturally, the amount and quality of knowledge received will depend on the messenger. Most often, extension agents may be necessary.

Users' attitudes toward nanotechnologies will depend on their knowledge, their feelings toward the technology, and any preconceived ideas they may have about it. Perceived benefits and risks will play an important role, as well as the acceptance of new technologies in general, and the users and sellers. As noted, studies of attitudes are related to consumers' perceptions of risks toward nanotechnology; in contrast, no studies have been done on acceptance and willingness to adopt nanotechnologies in the developing world.

While this focus reflects the priorities of research institutions today, this research asymmetry may reinforce the likelihood of a future nano divide. If consumers in developed countries are the drivers of research in nano food and agriculture, it would not be surprising if funding sources continue to focus on their demands and fears rather than those of poor rural populations. Furthermore, adoption studies provide critical information in the process to the ex ante assessment of new technologies and are therefore needed to inform decisionmakers of the potential benefits they could have in the future.

Further there is a potential financial risk in nanotechnology research similar to GMO's if they don't get marketed. To manage financial risk associated with these failures, large companies involved in GMO's have run huge programs so that their risks can be pooled across large numbers of research projects. If this occurs for nanotechnology research as the market matures there will be large economies to scale in research and little such research will be undertaken in developing countries as with pharmaceutical research.

Risks and Regulatory Issues

Environmental and Human Health Risks

Using nanomaterials is not inherently risky—many nanoscale materials are found in traditional food (such as proteins, milk)—but the use of certain nanoscale materials in agriculture, water, and food may have intrinsic risks for human use and consumption and/or for the environment (Chau, Wu, and Yen 2007; Davies 2010).

The aforementioned applications of nanotechnology (Section 2) are designed to mitigate various risks; however, to increase benefits for the poor, these applications should not themselves become a significant source of risk. Risks associated with the application of nanotechnology should be transparently presented. Utilizing a tiered risk assessment and risk management approach will allow the nanomaterials with low probability of exposure or low toxicity to be deployed first, while applications that appear to present more risk await the development of data for risk assessments or risk-mitigation strategies (FAO-WHO 2009).

The nanotechnology applications identified for agricultural production are not yet widely deployed and do not have a history of increasing environmental or human health risk. Nanofertilizers have not been linked to increased phytotoxicity or to an increased propensity for eutrophication of surface waters, but little research has been done. It is expected that just as conventional fertilizer products have been associated with some adverse impacts, nanofertilizers may present some of the same impacts. Nanoherbicides are likely to adversely affect plants to which they are applied. Because pesticidal products are highly regulated in developed countries, it is expected that risk assessments will be available for registered uses in these countries. These risk assessments will serve as a guide for assessing potential risks associated with use in developing countries. The fate and transport of both nanofertilizers and nanoherbicides will be critical to assessing their potential risk to the environment or human health.

While much has been written about the potential for nanosensors to detect hazards and mitigate risk (NNI 2009), there is a paucity of data on risks posed by deploying nanosensors in the environment. Nanosensors that are used in the field to gather data but not left unattended are less likely to pose environmental risk than they would if they were free to be transported off the agricultural site or inadvertently incorporated into another medium. Nanofeed additives and smart drug delivery systems will be used in conjunction with animal feeding or production and not dispersed throughout the environment. The applications are likely to pose little risk as long as they do not increase the risks from ingestion of the treated animals or pose a risk to humans applying the additives or drugs. The nanomaterials in nanocoatings are fixed within the coating matrix and are not likely to be released, greatly reducing the potential for exposure.

The nanotechnology applications identified for food safety and nutrition and water safety are limited in their potential risk to human health and the environment by their use patterns or design. Many of these applications are fixed within a medium (barriers, films, packaging, or filters) and are not likely to contribute to exposure unless they are physically or chemically released from the medium. Other applications consist of naturally occurring clays and minerals used only on animals through addition to animal feed and are not likely to present significant risk. The intentional addition of clays or synthetic nanominerals to bind to water-borne contaminants, such as arsenic, could result in risk to human health if the nanomineral particles are not completely removed from the water. A similar risk is associated with use of magnetic nanoparticles or other substances to absorb or aggregate harmful substances that are not removed from drinking water prior to its consumption. This risk could be mitigated by designing a system that does not allow use of the unfiltered water. A closed system that does not allow access to unfiltered water but only to treated water may be a successful way to mitigate this risk.

As with other risks, the risks created by using nanotechnology applications in developing countries to improve food and water safety, increase food security, and combat poverty must be balanced against the ongoing risks arising from inadequate diets and consumption of contaminated food and water.

More generally, several high-level reports have concluded that the main issue may be the lack of scientific knowledge on key factors needed for risk assessment, such as the toxicity of nanoparticles, the issue of bioaccumulation, or the lack of study on risks by ingestion (Bouwmeester et al. 2007; Royal Society/Royal Academy of Engineering 2004). The relatively low share of research funding on risks suggests that this may remain the case.[4] Furthermore, most risk research is currently on nonfood nanomaterials (Chau, Wu, and Yen 2007), which reflects the current focus of applications and needs (Byrne 2010; Taylor 2008). But this emphasis may result in new gaps of knowledge with future nanofood products coming to the market.

The general uncertainty around specific risks may favor different types of approaches. In some developed countries like Japan, South Korea, or members of the European Union that have relatively low trust in technologies, especially in the food sector, a precautionary approach is already apparent; pre-emptive regulatory measures are pushed forward, regardless of knowledge on potential risks. In contrast, some other countries, like the United States and perhaps emerging large economies, seem to put more emphasis on the potential of the technology and are approaching risk regulations more carefully, based on existing knowledge. So far, developing countries seem to be in between, looking at the potential but also waiting on risk assessment.

If confirmed, this geopolitical picture appears to increasingly follow the geopolitical situation that was observed with genetically modified (GM) food technologies (Gruère 2006a). Yet, obviously large differences between these and nanotechnologies exist, especially because GM crops basically use seed technologies and are therefore only associated with a very narrow range of potential risks compared with

[4] For instance, in the United States, 6.6 percent of the total public funding for nanotechnology research was devoted to risks (Schneider 2010b).

the much wider array of nanoscale applications. Moreover, in the case of GM food, only a few companies or research institutions are developing and commercializing products, concentrated in a few countries, while in nanotech a much larger number of actors will be involved. Lastly, there is a large and growing body of knowledge on the potential benefits of using nanotechnologies. In contrast, the potential risks of nanoscale technologies are much less known, and there is no real consensus on assessment methods (Bowman and Hodge 2009).

Perhaps the most important parallel between the two technologies relates to the consequences of sustaining the focus of public discourse on potential risks. Several authors have denounced the negative spillover effect of focusing on consumer perceptions and potential risks of using genetically modified organisms (GMOs) in developing countries (Nuffield Council on Bioethics 2004; Paarlberg 2009). Similarly, increased attention on risks in developed countries in the debate on nanotechnology is bound to threaten the effort of using nanotechnology in the developing world, despite its potential importance in the future of these countries (MacLurcan 2005). Court et al. (2004) believe that this could create a "nano divide" between rich countries that do not really need them and actual needs in developing countries and this term has now become a common term in articles on the ethics of nanotechnology.

Regulations

Currently, there is no specific regulatory framework in developing countries. In fact, developed countries have not introduced specific regulations on nanotechnology either (OECD 2010); they rely on existing legislation to regulate nanomaterials.[5] Changes to current regulatory systems are still largely debated at present (for example, Bowman and Hodge 2009).

Several high-level panels have recommended how to approach the issue of nanotech risk regulations, especially as it pertains to food. The Science and Technology Committee of the House of Lords (2010) has suggested several ways to address the current situation, including a voluntary code of conduct in the presence of uncertainty, a mandatory precommercialization assessment of risk for new nano food, the use of existing risk assessment methods supported by a much-increased research investment effort in risk assessment and detection methods, and the revision of risk regulations every three years. The European Food Safety Agency supports the use of conventional risk assessment while acknowledging the limited knowledge on exposure from nanofood applications (Harrington 2010a; Kuzma 2010). Others provide much more detailed recommendations on definitions, key principles, and regulatory approaches for different types of risks (Chau, Wu, and Yen 2007; Walsh and Medley 2008) and the possible role of codes of conduct (Bowman and Hodge 2009).

Given current uncertainties in risks and risk assessment procedures, and the possibility of consumer backlash, some analysts have suggested that regulations should not be introduced too early nor too late (Sandoval 2009; Sylvester, Abbott, and Marchant 2009). The objective should be to strike the balance between too much precaution in the face of incomplete information, leading to disinvestment and reduced public confidence, and not considering risk too seriously, especially as knowledge grows (Sylvester, Abbott, and Marchant 2009). The most important objective should be to increase investment in risk research.

In developing countries, building on existing institutional capacity should be seen as a priority. In particular, taking advantage of similarities in nanotech and biotech may help reduce barriers to entry (Niosi and Reid 2007). A growing number of developing countries have introduced biosafety regulations after years of efforts and funding, and many more are in the process of doing so, after years of internal struggles. In fact, Uganda already refers to their biosafety office when being questioned about the safety of nanotechnology products (Ngayta 2009). While this makes sense for countries like Uganda or Kenya where the biosafety office is under the ministry of science and technology, it may be difficult in other countries where the biosafety regulations are implemented solely by representatives from the ministry of the environment, which lacks expertise in food safety.

[5] Canada was reportedly the first country to introduce mandatory reporting of nanomaterials (Sanderson 2009).

More generally, while acknowledging that there are large differences, lessons could be learned from the challenges observed in setting up agricultural biotech regulations in developing countries. Several key issues in the framing of risk management procedures, discussed at length in the case of agricultural biotechnology, will likely come back to the forefront, such as the needs for transparency, public education, and liability and redress (Anane-Fenin 2008). The observed high costs of compliance with regulatory approvals in biotechnology, which act as barriers to public technologies and competition, should be avoided in developing countries at the risk of limiting technologies to a few multinational innovations (Falck-Zepeda, Cavialeri, and Zambrano 2009). Regulatory approaches should also aim at being more predictable than in the case of GMOs, as predictability is one of the determining factors to the commercialization of nanotechnology in any given country (Chun 2009).

At a higher level, the large influence of the Cartagena Protocol on Biosafety in the design of biosafety regulations in virtually all developing countries underscores the importance of international agreements (Secretariat of the Convention on Biodiversity 2000). The Protocol's recognized weaknesses (Paarlberg 2009), such as a deliberate strict precautionary approach (Gruère 2006a), a limitation to environmental risks from transboundary movements of GMOs that is bound to have more effect on trade than on the environment (Redick 2007), and the fact that it does not include all major GM producers (Gruère and Rosegrant 2008), should all be avoided in any potential international framework on nanotechnology risks. The lack of risk assessment capacity and porous borders in African countries requires countries to group their efforts into regional biosafety regulatory frameworks and should be followed and adapted to nanotechnology. More generally, harmonization schemes based on international consensus—like the voluntary standards at the Codex Alimentarius—rather than on limited-focus groups are more likely to avoid future trade disputes.

Risk Perceptions and Consumer and Market Acceptance

Risk perceptions are critical to the future acceptance of the technology globally (Kuzma and VerHage 2006), not only because they will influence policies and investments in major countries and their followers, but also because they tend to be the result of social and psychological factors and therefore they are not always easy to change even with increased knowledge (Satterfield et al. 2009).

A recent meta-analysis on risk perception around nanotechnology shows that despite the general lack of knowledge, the public is still fairly positive about the potential of nanotechnology (Satterfield et al. 2009).[6] While increased familiarity seems to be correlated with potential benefit perception, unfamiliarity does not correlate with increased perceived risk. The main conclusion of Satterfield et al. (2009) is that it is too early to conclude whether nanotechnology will follow observations made with other technology; perceptions are still too "malleable" to be evaluated. More generally, they note that many questions remain about the perception of risk in nanotechnology and that there is a significant gap of knowledge in existing literature. Furthermore, risk perceptions are still bound to change with growing awareness about the technology (Kahan 2009). Attitude changes are more likely when consumer knowledge is low, as it is with nanotechnology (Cope et al. 2010).

With nanofood applications in agriculture and food, indications are that developed-country consumers tend to be more averse than others (Lyndhurst 2009), especially to the applications that are "closer to their bodies" (Federal Institute for Risk Assessment 2007). Still, not all products are associated with the same levels of risk; the perceived benefits and the fact that a product is perceived as closer to nature affect acceptance (Siegrist, Stampfli, and Kastenholz 2009). For instance, focus groups showed that while consumers in Germany and Switzerland may be positive about food safety improvement devices, they tend to be much more reserved about nanoengineered ingredients (NanoBio-RAISE 2007). A consumer experiment also showed a general aversion of German consumers toward nanofood products, especially those with nanoingredients relative to nanopackages (Marette et al. 2009). Consumers are more averse when they learn that there may be potential health risks. Marette et al. (2009) also show that in the

[6] More specifically, Satterfield et al. (2009) find that of the surveyed public in the U.K., the United States, and Canada, three times as many believe that the benefits of nanotechnology will outweigh their risks than those who believe the opposite.

current market, nano consumer applications such as that for orange juice they would not be profitable.

External factors could play a role in shaping future acceptance in key food markets that will largely affect the future of technologies worldwide. Several civil society groups have explicitly supported a complete ban of nanotechnology in food and agriculture (ETC Group 2004; Lyons 2010; Miller and Senjen 2008), and their position may prove influential in developed-country markets, as in the case of GMOs. Although their efforts have not been fully effective thus far, they may push toward reduced commercialization. The consequence of such outcome would further drive the divide on technology, as developed nations can afford to continue to invest in nanotechnology with strict limitations to nanomaterials production, but developing nations often cannot (Court et al. 2004). The growing voice supporting the interdiction of nanotechnology in organic agriculture (Paull and Lyons 2008),[7] while expected, may also push a growing share of consumers to find ways to avoid nanotech food applications with larger spillover effects worldwide. However, it should be noted that many of the nanotechnology applications with great potential to affect the poor do not involve nanofoods.

As risk communication will have a significant role to play, industry and government representatives in Western countries are aware of the need to avoid the mistakes associated with GMOs. Strategies should particularly pay attention to who delivers the message and whom the target is, as trust and sociocultural background largely influence the effectiveness of communications on new technologies (Sylvester, Abbott, and Marchant 2009). In particular, in many countries, risk-related messages from governmental authorities will not necessarily result in increased acceptance and could in fact contribute to growing aversion toward nanofood applications. Furthermore, the message itself should focus on consumer concerns, as much as possible, and include information about the risk management process and the potential uncertainties (Cope et al. 2010).

The possibility of introducing blanket labeling requirements on nano products could also have significant effects beyond developed countries to technology deployment and regulations in developing countries, as observed with GM food (Cohen and Paarlberg 2004; Gruère 2006b). Although it is being demanded by a number of civil society groups,[8] mandatory labeling could shape public acceptance of nanotechnology (Chun 2009) and create a stigma effect with industry shunning away from nanotech products (Sandoval 2009), as observed also with GM food (Carter and Gruère 2003; Marchant, Cardineau, and Redick 2010). This is one of the main reasons why it does not appear to be a satisfying regulatory recommendation. A report by the U.K. House of Lords suggests instead of labeling, developing a public register of approved nanotech in food with increased public information campaigns (Science and Technology Committee of the House of Lords 2010). It should be noted that many applications of nanotechnology do not involve food, although they may involve agricultural methods.

As observed with Magic Nano aerosol,[9] consumer products that are labeled as nano but are not actually nano based could also create significant negative advertising for nano (Helmus 2006). Taiwan's unique initiative to certify products with a "Nano Mark" was introduced to avoid such situations (Chau, Wu, and Yen 2007). Myths are also rapidly developing associating nanotech with "magic," as seen in Uganda in the case of a small glass (Ngayta 2009).

More generally, as with GM food (Gruère and Sengupta 2009), food companies' decisions to use or avoid nanofood will be determining factors in the future of nano consumer products (Scrinis and Lyons 2007). The fact that large food companies have already decided to avoid publicly declaring that their products are based on nanotech for fear of consumer backlash (Berger 2008; Boggan 2006; Chun 2009;

[7] Resulted in aa recent decision to exclude nanotechnology in the Canadian organic standard (Organic and Non-GMO Report 2010).

[8] For instance, in the United States, the Consumers Union at the federal level has explicitly requested mandatory labeling of nanoengineered food (Cairns 2006). At the international level, Friends of the Earth also calls for immediate labeling of nanofood products, if not a moratorium on all nanotech ingredients in the market (Miller and Senjen 2008).

[9] Magic Nano was a bathroom cleaning aerosol released in Germany in the first few years of the 21st century and recalled due to reports of sicknesses of customers. The recall resulted in large negative press coverage of nanotechnologies in Germany, even if the products did not contain any nanoparticles, as revealed by the German Federal Institute for Risk Assessment. Interestingly, the government report was much less covered than the recall.

Davies 2010; Shelke 2006)[10]—despite the fact that they have set up large nanotech research development programs—is a sign that a repeat of the GM food scenario is a distinct possibility.[11,12] Furthermore, companies' positions seem to be relatively well established on information disclosure; the U.K.'s Food Standards Agency believes that a mandatory disclosure regulation there would result in exodus from the U.K. (Harrington 2010b). The direct implication of this secretive disposition is that the general public, and even the scientific experts, do not know which applications are being developed and used in the food sector (New Scientist 2010). The indirect consequence may be that the public perceives that potential risks drive companies to remain secretive. While these may be short-term considerations, a continued reluctance by large companies could pre-emptively force nanofood and agricultural products out of the market and decrease the likelihood of adoption of related technologies in the developing world.[13]

In contrast, increased consumer awareness and information on nanotechnologies and their risks are supported by food companies (Byrne 2010; Sandoval 2009), as it will benefit them both directly via potentially higher acceptance from higher familiarity (Satterfield et al. 2009) and indirectly by avoiding costly liability settlements (Howells 2009). Private stewardship may also play a role, as seen in the growing numbers of voluntary codes (Bowman and Hodge 2009).

Market Risks

Apart from human health and environmental risks, economic risks may also play a role in the success of nanotechnologies. GM technologies have shown that even for technology intended for domestic use on nontradable goods, trade considerations highly matter in decisionmaking in many developing countries (Gruère and Sengupta 2009).

Nanotechnology applications pose three main concerns. First, nanotech products could face barriers to entry due to the presence of import regulations or importers' own policies limiting the use of nanotech. For instance, the reported use of nanocoating on produce exported from Latin America to the United States (Schneider 2010a), while not violating current regulations (that do not mandate any assessment), triggers interest for import regulations by U.S importers. Export barriers can effectively influence risk-averse policymakers in developing countries[14] and push them to avoid any sensitive research investment (Gruère 2009).

Second, several nongovernmental organizations believe that nanotech will have significant negative economic effects on the poor via increased productivity in the North, and depressed prices for commodities (ETC Group 2004; Scrinis and Lyons 2007). This argument is not new but would only be valid in the agricultural and food sector if nanotechnologies do in fact increase agriculture productivity, leading to higher production levels. While certain innovations may lead to reduced input use, pure productivity increase does not seem to be the main focus of current research in nanoscale science, so this may be less important in the short term.

Third, there are indications that certain innovative applications of nanotechnology could depress demand for commodities, having potential economic effects on commodity-dependent developing countries (ETC Group 2005; Meridian Institute 2007). In particular, in agriculture, if the development of nanotextile applications were to favor synthetic fibers instead of natural fibers, this may have an effect on the cotton market with possible tremendous implications in a large number of vulnerable developing

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[10] In the case of packaging, Byrne (2010) notes that European companies may also lack economic incentives to move forward more aggressively.

[11] A singular example is that of Kraft Foods, which went as far as changing the name of their Nanotek Consortium (a nanofood research center proudly opened in 2000) to Interdisciplinary Network of Emerging Science and Technologies (INEST), most likely to avoid public awareness on their nanotechnology and food research activities (Berger 2008).

[12] Boggan (2008) cites a Unilever representative as saying that consumer perception is very important, keeping in mind the case of GM food in Europe as a main example for caution. Unilever is in favor of labeling of nanoparticles if labels are "meaningful" and specific" (Watson 2010).

[13] This includes products that may not face any export risk, as shown in the case of GMOs in Africa (Gruère and Sengupta 2009).

[14] See Gruere and Sengupta (2009) as an example with GMOs.

countries, particularly in central and West Africa and South Asia, where millions of families depend on cotton. Similarly, the development of synthetic rubberlike materials could affect the demand for natural rubber with effects on countries with large rubber tree production, especially in developing countries of Southeast Asia.[15]

While nano substitutes are serious concerns that call for specific anticipatory responses, they should be examined individually on their own merit and addressed as such. For instance, other factors could compensate for the substitution effect of nanotextiles, notably the successful promotion of cotton garments in developed countries (for example, U.S. ability to keep a steady share of natural fibers on the garment market) and the demand from rich countries for natural fibers. Furthermore, current research at Cornell University on improved processing of cotton fiber at the nanoscale (to produce electrospun cellulose) could in fact lead to increase in demand of cotton lint. Similarly, the substitution of rubber by synthetic material would have to be economically justified. Countries with rubber production may also push toward the marketing of natural rubber. These points suggest that a case-by-case approach[16] be followed to determine whether commodity-dependent developing countries are at risk of facing demand shifts in the near future.

More generally, market risks should be managed based on their merit. There is some early evidence that the media could fall into overexaggeration of the phenomenon,[17] creating fears that could be detrimental to future useful technological development. As noted by Gruère and Sengupta (2009), commercial risks differ considerably from health and environmental risks, do not share the same direct consequences, are less uncertain and not irreversible, and therefore should be managed differently.

[15] In South Africa, the issue relates to the lower use of minerals, like gold, depressing the rents from extraction with potential negative effects on the whole mining industry (Claassens and Motuku 2006).

[16] See the approach suggested in Gruère and Sengupta (2009).

[17] A news release in the Philippines cited a briefing of the nongovernmental ETC Group to state that “nanotechnology could kill small farmers” (Mai 2008).

4. DISCUSSION: WHAT ROLE FOR THE NEW CGIAR?

Much research has quantified the benefits of research in the agricultural sector. Past experience with agricultural growth indicates that the diffusion of better technologies in the form of better husbandry practices and livestock and crop varieties has been responsible for agricultural growth even with limited national research investment. Indeed, past examples include a country that recognized the difficulties of direct transfer of a desired agricultural technology and would often expand its agricultural research programs to facilitate the indirect transfer of the technology by adapting technology to the specific needs of the country (Judd, Boyce, and Evenson 1986).

Currently, agricultural technology originates from multiple sources, which may be public or private, domestic or foreign. Pray and Echeverria (1991) suggest that a distinction between foreign and domestic and between public and private is relevant when analyzing each sector’s activity. Table 1 summarizes the various institutions that may be involved in the generation of agricultural technologies. It is possible that the changing institutional environment in which agricultural technologies are being created and the increasing lack of available public-sector money will create a situation with further changes in the actors involved in research and an increasing need for private-sector involvement in research (Hayami and Otsuka 1994). This situation has occurred in many types of biotechnologies and may also with most nanotechnologies.

Table 1. Institutions involved in the generation of technologies

Institutional Location		
	Domestic	***Foreign***
Public	Ministry Research institute Research council University	Ministry Research institute University International Agricultural Research Center (IARC)
Private	Cooperative Foundation Commodity institute Plantation Processing company Input company	National company Multinational Cooperative

Source: Pray and Echeverria 1991, 347.

Different factors affect research investments by the various sectors, depending on whether the nature of the research (1) is basic or applied; (2) embodies a public-good problem; (3) is such that the returns may be appropriated by others than those involved in conducting research due to the lack of an appropriate enforceable legal system; (4) creates a situation involving either the creation or the correction of a market failure; (5) relies on access to traded inputs that are currently affected by price distortions or trade barriers; and (6) is such that the market structure (vertical integration, oligopoly, and so on) plays an important role in its generation. Table 2 summarizes the various factors influencing the costs and returns to agricultural research.

Table 2. Factors influencing the costs and returns to agricultural research

Item	Factors Influencing the Costs and Returns Economic	Government Policies
1. Returns to Research	Market size: domestic and international Demand elasticities Rate of market growth Level of economic development Income elasticities Capability of being appropriated Nature of technology Nature of market	Ag. sector policies Price policies Macroeconomic policies Trade policies Monetary policies Exchange rate policies Fiscal policies Intellectual property legislation Antitrust policy Degree of legal enforcement
2. Cost of Research	Level of industrialization Supply and demand of agricultural inputs and technical manpower Availability of nonprivate research output: domestic and foreign Quality and costs of research inputs Extent of nonprivate research	Ag. sector policies Price policies Technology policies Macroeconomic policies Fiscal policies Policies on foreign investments / ownership Public funding of research Intellectual property legislation

Source: Umali, Feder, and de Haan 1992.

The development of new technologies may bring not only new benefits to a society but also costs. Umali, Feder, and de Haan (1992) note that the extent to which the benefits from the research activity exceed the costs depends on the type of incentives for both public and private investment in agricultural research. Below we summarize some of the economic principles that affect the type economic incentives faced by those involved in agricultural research.

Basic and Applied Research

Basic research is considered to be the original investigation into an area that results in advancement in scientific knowledge. It is done for its own sake, with no particular application in mind, and it may not necessarily result in a commercial application (Mansfield et al. 1977). Some of this basic research, however, may develop into commercial applications over a longer period of time. The often lengthy delay between research and application makes it very difficult for a company to keep the information secret. This is because knowledge can leak out either through lateral moves of scientists between companies or the sharing of major breakthroughs among scientists. For this reason, among others, private firms devote relatively small amounts of resources to basic research compared with their overall research budgets (Mansfield et al. 1977). Because basic research is considered a public good, often it is necessary for the public sector to invest in this type of research.

Applied agricultural research, on the other hand, is aimed at a specific practical commercial application and involves the search for applications of technologies, often basic in nature, that have been developed. The dividing line between who does basic research and who does applied research is often unclear. This is because research and development often are part of the process leading to a successful technological innovation. If the benefits are appropriable factors into applied research and the payoff is uncertain and distant, then this type of research often becomes part of the public domain (Mowery and Rosenberg 1989).

There are certain situations in which the benefits of applied research cannot be appropriated by the private firms. Therefore, the private sector is not always interested in undertaking such research even in situations where it might be considered socially profitable. In these situations, even though this research may indeed produce knowledge that may result in a substantial increase in productivity and alleviate some of the externalities of production, it is not done. This is because the process cannot easily be sold to another company for the cost of the research (Jarvis 1986). In these situations the private sector has no incentive to undertake the research because the product is a public good, and the public sector therefore needs to respond to the research need.

Public Goods and Private Goods

Products can be classified in economic terms as either public goods or private goods. Public goods are characterized by nonrival consumption and nonexclusion. Such goods are considered to be nonrival when their consumption by one person does not hinder their consumption by another, given the current level of production. Such goods are considered nonexclusive when the costs of exclusion are so high that it is practically impossible to exclude others from using them. Private goods, on the other hand, are characterized by both rival and exclusion principles. These goods are rival in the sense that one individual's consumption of the good precludes its consumption by another. They are excludable in the sense that the producer may restrict their use to those willing to pay for them and exclude their use from those not willing to pay for them. The nonexclusivity and nonrivalry nature of many public goods often gives rise to the free-rider problem.

The private sector invests in research in areas where it expects the risk adjusted present value of the benefits derived from the research activities to exceed the risk adjusted opportunity cost to generate them. Pray and Fuglie (2001) identify three key determinants of agricultural research investments by profit-seeking firms: (1) the size of the potential market for new technology; (2) the ease of developing improved technology for a given level of research investment; and (3) the ability of a firm to capture the returns to research investments and protect intellectual property, sometimes called "appropriability." In terms of nanotechnologies we suggest that those technologies most important to the poor are those that would lead to improved agricultural productivity, enhanced nutrition in food, and improved food and water safety.

Technology Transfer

Closely related to the investment in research that generates new technology is the issue of *technology transfer*, which is the process by which technology moves from one location to another. The knowledge may be embodied in technical equipment (machines), people (engineers, scientists, and technicians) or publications. The transfer may occur in a multitude of ways: through patents, the flow of technological information, educational programs, the movement of equipment, the export of productive processes, or the distribution of products. The speed and extent of the transfer are often dependent on the investment by the sending and receiving regions (Evenson 1994). A major benefit of technology transfer is that a firm or person desiring a technology need only invest minimally or not invest at all in its own research and development in order to obtain the benefits of technology, especially if the countries involved have similar environments. Conditions that may encourage transfer of technology are similar physical and institutional environments, adaptive research, and the absence of market distortions that may make the new technology seem unprofitable (Jarvis 1991).

Recent advancements in communication and transportation have enabled technology and scientific knowledge to move across national borders more rapidly than in the past. This ease of transfer has in part created an environment where innovating companies may find it more difficult to appropriate the returns to their research overseas due to lack of universal legal controls (Rosenberg 1990). The increasing cost of new product development, nontariff trade barriers, and the desire to import certain strategic technologies have thus led some companies to increase the amount of their overseas collaboration (Mowery 1992).

The establishing of a company overseas or the utilization of foreign subsidiaries enables technology to be transferred in a variety of ways. For instance, a multinational company might train operatives and managers (technical assistants) who communicate various types of nonspecific information to local users of a technology. These technical assistants may have the capabilities to engineer technologies that can be adapted to the availability of local resources and inputs into production, or to help the users of their products to use them more effectively and help suppliers upgrade their technology. For instance, poultry-breeding companies send special trainers to provide technical assistance to those who buy their lines (Narrod et al. 2000). This type of interaction enables a company to reduce some of the transaction costs associated with the lag between the initiation of basic research and the widespread adoption of the finished product.

Current Research and Development Efforts in Agriculture Production, Improved Nutrient Content in Food, and Food and Water Safety and Nanotechnology Opportunities

Historically, in agriculture and associated research, to improve the nutrient content of food as well as food and water safety research, the private and public sectors have complemented each other. The public sector has largely focused on areas where private-sector incentives have traditionally been weak or have become weaker as incentives changed. Though research to improve agricultural productivity has been both supply driven and demand driven, most of the research to improve nutrient content and food and water safety historically has been directed at supply-side questions (such as technologies to ensure proper detection of pathogens or biofortification of food). Efforts are increasingly being directed at understanding areas where there is the most demand for biofortified food and food and water safety (such as estimating the willingness to pay for food safety attributes of food and water), yet still only minimal studies exist.

Research efforts by the public sector in these areas has mostly been directed at basic research (original research that advances scientific knowledge but with no immediate commercial application), while the private sector has focused on applied, market-oriented research. The relative importance of the public and private sectors in these research areas based on a qualitative assessment of the kinds of activities carried out by each sector is depicted in Table 3, as well as areas where current nanotechnology research may provide solutions to help the poor.

In areas of increased agricultural productivity both sectors have largely been involved, with the private sector focusing on efforts where they could get a return, and the public sector focusing on efforts where the private incentives were weak. Nanotechnology research areas that would benefit the poor are nanoherbicides, nanofertilizers, and soil amendments that regulate water availability.

In the area of disease protection and nutrition, much of the private-sector research also has been where they could obtain economic returns from investments, and the public sector has focused on basic research on pathology, nutrition, and metabolism. Nanotechnologies that could benefit the poor are in terms of nanosensors to detect contaminants, pests, nutrient content and plant stress, nano feed additives, smart drug delivery systems; research on nanocoatings could reduce the concentration of food-borne pathogens, for instance, in poultry houses.

In the area of food- and water-borne hazards, both sectors have made large research investments. Private research has focused on developing products in which intellectual property rights can be protected, such as new machinery and diagnostic kits. Public research has emphasized basic studies on antibiotic drugs, microbial pathogens, pesticides, mycotoxins, parasitic disease, and heavy metals. The public sector has also conducted research on pathogenicity, epidemiology, and ecology of microbial pathogens. The public sector increasingly conducts research in risk assessment and aids the private sector in the development of new control methods in agricultural production and processing. Research that would benefit the poor includes that on nanosensors to detect microbial pathogens and chemical contaminants in food or water and at various points along the supply chain and research on how nanotechnology applications could become part of a Hazard Analysis & Critical Control Points (HACCP) assessment. In addition, there is research on nanotechnology barrier applications to improve packaging, the use of antimicrobial nanomaterials to prevent microbial contamination along the supply chain, and nanosensors in food packing to alert poor consumers that there is a problem.

In the area of procedures and standards, the private sector has played an active role in developing its own guidelines for processes, which may be used as internal standards or specified as a part of contracts between firms. For example, the private sector provides some product standards efficiently, like those of the International Organization for Standardization. In addition are "soft-law" approaches or third-party marketing requirements, like those currently demanded by Walmart. In this case there is no market failure since the benefits are internalized by the consumers, and hence there is a payoff to providing these standards. When information is asymmetric, then the privately provided standards mediated through third-party certification could depict quality, or publicly provided process and product standards based on research could be employed to signal quality. Research on nanotechnologies in these areas that may be beneficial to the poor includes studies on low-cost nanosensors that can detect problems from which data could be collected to use in risk analysis, as well as the development of nano-antimicrobial coatings to protect food processing equipment.

The public sector has also conducted some research to develop new means of monitoring the hazards and to assess the feasibility, benefits, and appropriateness of kinds of standards for regulation. There is a clear connection between this type of research and risk assessment, cost–benefit analysis, cost-effectiveness analysis, and risk communication. For the most part, the public sector has been the primary actor involved in this type of research to inform the regulatory process. Food- and water-borne disease surveillance and the associated public health research are a unique public-sector responsibility and are carried out at the national, state, and local levels. Research on rapid nano-based methods to detect chemical contaminants or disease organisms in food and water and on nanosensors to alert public health facilities of environmental conditions associated with food- or water-borne disease would benefit the poor.

Table 3. Current roles of the public and private sectors in improving agricultural productivity, food nutrient content, food and water safety research, and types of nanotechnology opportunities in specific areas

Area	Private Sector [a]	Public Sector [a]	Nanotechnology Opportunities
Research to improve agricultural productivity	*** Applied breeding where technology can be protected through trade secrets (hybridization), market share, or patents on genetically modified traits	*** Basic studies in genetics, physiology, and biological efficacy Applied breeding where private incentives are weak	Research on nanoherbicides that can be time released upon occurrence of an environmental trigger Research on nanofertilizers to reduce nitrogen loss
Disease protection and nutrition	*** Applied research on products that can be patented or protected through trade secrets	*** Basic research on pathology, nutrition, and metabolism Applied research on management systems to control disease, and in livestock also on improved feed efficiency	Research on nanosensors to detect contaminants, pests, nutrient content, and plant stress Research on nano feed additives that bind with harmful bacteria to reduce food-borne pathogens Research on smart drug delivery systems to detect and treat an animal infection or nutrient deficiency Research on nanocoatings to be used in poultry houses to reduce concentration of food-borne pathogens
Research on *food- and water-borne hazards* along the supply chain	** Applied research to ensure products have acceptable levels for shelf life and handling Applied research on hazards leading to development of new tests to detect hazards	*** Basic research on antibiotic drugs, microbial pathogens, pesticides, mycotoxins, parasitic diseases, and industrial and environmental contaminants Research on pathogenicity, epidemiology, and ecology of hazards Development of risk assessment models for hazards	Research on nanotech sensors to detect microbial pathogens and chemical contaminants in food or water at various points in the supply chain Research into how nanotechnology applications could become part of a hazard assessment for critical control points along the supply chain

Table 3. Continued

Area	Private Sector [a]	Public Sector [a]	Nanotechnology Opportunities
Research on *technologies* to measure and mitigate food- and water-borne hazards along the supply chain and identification of crucial infrastructure needs	*** New equipment or methods to prevent them where market or regulatory incentives exist (for example, antimicrobial rinses)	*** Development of new control methods in agricultural production and processing	Research on developing rapid, user-friendly field test kits that could be used in circumstances where it is impractical to conduct a traditional chemical or microbial analysis that might require sophisticated equipment or a laboratory Research on nanotech barrier applications (films and packaging to reduce exposure of food/water/beverages to microbial or chemical hazards or to manipulate the environment within the packaged product to reduce microbial growth such as nanoclays to reduce/eliminate oxygen contact with beverages) Research into the use of antimicrobial nanomaterials to prevent microbial contamination along the supply chain (silver nanoparticles embedded in food contact surfaces or food packaging material to reduce microbial growth) Research into nanosensors in food packaging to alert consumers or others in the supply chain of unacceptable levels of microbial pathogens or chemical hazards

Table 3. Continued

Area	Private Sector [a]	Public Sector [a]	Nanotechnology Opportunities
Food production and processing procedures and standards	*** Applied research leading to the establishment of standard operating procedures, good manufacturing practices, and HACCP systems	*** Research to develop new methods of monitoring or to determine appropriate standards for regulation	Research into how nanotechnology applications could become part of a hazard assessment for critical control points along the supply chain Development of low-cost, rapid nanosensors to detect the presence of microbial or chemical hazards in food or water Development of nano-antimicrobial coatings for food processing equipment or antimicrobial paints for rooms where food storage or processing occurs Development of nanofilters to purify water used in food processing
Food- and water-borne disease surveillance	* Little involvement unless customers are affected or regulations specify minimum environmental standards (such as in the case of industries that pollute water resources)	*** Monitoring and investigation of disease incidence and outbreaks Research to understand public health and environmental health consequences	Development of rapid nano-based methods to detect disease organisms in food or water—such methods would not require sophisticated equipment or a laboratory Development of nano-based test kits to diagnose diseases resulting from food or water contamination Development of nanosensors that will alert public health facilities of environmental conditions associated with food- or water-borne disease

Source: Adapted from Narrod et al. 2007.
Note: [a] asterisks indicate relative emphasis on research by sector: *** major focus of research; ** important but secondary focus of research; * little research conducted.

What Can the CGIAR Do?

Clearly the nanorevolution is occurring, and though there is no precise figure of investment in nanotechnology as mentioned earlier, a largely cited consultant report estimated about $20 billion has been invested (Helmut Kaiser 2006). Whether or not the benefits of these advancements reach the poor will depend on whether public research institutions, technology developers, and national and international donors are able to overcome constraints associated with investment, research and development, regulatory approval, commercial release, distribution, access, and adoption. Currently the CGIAR system is not involved in nanotechnology; however, in the past it has been heavily involved in understanding the returns from public and private research in terms of both the green revolution, biotech revolution, and livestock revolution and the complementary roles that both the public and private sectors bring to the research agenda for which the poor have benefited. In addition it has been involved in assisting countries in preparedness with regard to biosafety issues as it is difficult to transfer technologies that have not had regulatory approval even for developing countries.

The CGIAR system was formed to mobilize science to conduct research to benefit the poor and generate global public goods. The CGIAR works with universities and national agricultural research institutes to implement research that produces international public goods that will benefit the poor. Though the research agenda has evolved over time from the original focus on increasing productivity in individual food crops to a broader focus, it has recognized that with growing attention being placed on the use of improving the nutrition of food and improving food and water safety by both developed and developing countries, the sustainability of the system with small producers and processors depends critically on enhancement of nutritional and food and water safety attributes of production and other processes in the food chains involving small farmers and processors. Nanotechnologies present a new opportunity to help improve agricultural production and the nutrient content of food, as seen in Table 3, as well as to address many food and water safety issues and to improve the livelihoods of the poor. However, many nanotechnology opportunities at this time seem unlikely to be accessible to the poor in the immediate future. It is, however, likely that a number of technologies will be beneficial to the poor in the future and lead to reduced poverty or food insecurity if challenges such as regulatory approval, commercial release, distribution, access, availability, adoption, and proper use by the poor are addressed as these innovations are occurring. During this lag time, the CGIAR centers could pay a pivotal role in facilitating nanotechnology efforts to overcome such challenges.

In Table 4, we present some additional areas that the CGIAR could help facilitate access of the poor to the benefits of the nanotechnologies being developed. First, currently education is undertaken in a limited fashion within industry, but more broadly by the public sector to serve different parts of the food chain. Both the public and the private sectors have conducted some research on assessing the demand for food safety. The public-sector research on understanding the cost of food- and water-borne disease has been a derived demand to help prioritize their regulatory efforts. The private sector has focused its efforts on trying to understand the demand for food safety to implement technologies or management processes at critical points along the supply chain to ensure their competitiveness. One area the CGIAR system can work is in the provision of educational material by producing information on how nanotechnology applications can improve agricultural yields or decrease food spoilage or improve water at the farm or household level, by collecting information on people’s willingness to pay for such technologies, and by conducting studies on technology transfer and adoption.

Another area of importance is analysis to support agricultural and food policy and regulatory efforts in a developing-country setting. Currently, even in a developed-country situation, the private sector has little involvement unless regulatory action affects profit. The public sector tends to do applied research needed for conducting risk assessments and cost–benefit analyses. Most developing countries lack this capacity. The CGIAR centers could facilitate this process using data from nanotechnology-based sensors to create hazard maps of areas where natural occurrence of chemical hazards (such as arsenic), biological hazards (for example, concentrations of aflatoxin), or hazards to producing agricultural crops (for example, drought-susceptible soils) occur and could provide information on where nano-based risk mitigation may be profitable to the community (for example, areas where nanosoil amendments may increase water retention and crop yield).

Impact assessments are strength of the CGIAR. Most efforts to evaluated technologies do not necessarily look at the adoption and monitor and evaluate the impact of using new technologies. As done with past technologies, ex ante and ex post evaluations have a role to play in helping to set up priorities and continued support for technologies. These would encompass the potential technology effect and demand-related issues. For instance, research is needed to evaluate how nanotechnology applications could become part of a hazard assessment for critical control points along the supply chain that the poor are involved in. We believe that CGIAR centers can take a lead in strategic assessment of nanotechnologies and provide support to the funding and decisionmaking in this area.

More generally, issues of nanotechnology governance to overcome the challenges outlined in Section 3, such as finding proper incentive structures for investment, designing and implementing regulations, and anticipating and managing market risks, are key global public research areas in which the CGIAR has a comparative advantage. Neither the public nor the private sector tends to conduct analysis into policymaking and how alternative systems could affect their involvement and success in using new technologies.

Table 4. Areas where CGIAR can play a role

Area	Private Sector [a]	Public Sector [a]	Nanotechnology Opportunities
Education, technical assistance, technology transfer, and adoption	** Provision of technical service independently or along with sales of a food or water safety product (such as vaccine or water treatment/irrigation technology) Industry organizations may provide training to members to increase their awareness.	*** Education of farmers, consumers, food service workers, industry managers, or small firm owners through publicly supported programs Applied research to understand factors and prioritize research efforts and identify ways to improve adoption	Development of educational material providing information on how nanotechnology applications can improve agricultural yield or decrease food spoilage or improve water supplies at the farm or household level Development of assistance programs and deployment of experts to show how to use nanotechnology-enabled agricultural applications and food applications
Analysis to support decisionmaking, policy design, and standard setting in food and agriculture	* Little involvement unless regulatory actions affect profit; then conduct research to submit to public in an effort to alter regulatory agenda, or when the regulatory agenda is set, conduct research on cost-effective strategies to comply with the public regulations	*** Applied research in the development of risk assessment, cost–benefit analysis, and cost-effectiveness analysis in support of regulatory analysis and standard setting; research on risk ranking for priority setting, and identify risk–risk tradeoffs, research to identify effective ways to communicate risks to public	Nanotechnology could provide better tools for detecting the presence of hazards or identifying populations that have been exposed to microbial or chemical hazards for which the data can be used in risk analysis. Nanotechnology-based sensors could be used to create hazard maps of areas where natural occurrence of chemical hazards (for example, arsenic), biological hazards (such as concentrations of aflatoxin) or hazards to producing agricultural crops (for example, drought-susceptible soils) occur and provide information on where nano-based risk mitigation may be profitable to the community (areas where nanosoil amendments may increase water retention and crop yield).
Governance issues	Basic or no research	Generally none	Designing incentive mechanism for public technology research and development, overcoming access and distribution barriers, setting up and support implementation of risk regulatory frameworks, management of market risks

Source: Authors.
Note: [a] asterisks indicate relative emphasis on research by sector: *** major focus of research; ** important but secondary focus of research; * little research conducted.

5. CONCLUSIONS

In this paper we analyze the potential opportunities and challenges of agricultural, food, and water nanotechnology for the poor. We first provide a rapid assessment of key technologies that could have a large impact on the poor via increased agricultural productivity, improved food and water safety, and nutrition. We then review some of the main challenges to their deployment and adoption by the poor, and discuss the potential role of the CGIAR in this regard.

Although there are discrete indications of enthusiasm for nanotech and agriculture in developing countries (Anane-Fenin 2008; Sreelata 2008; Warad and Dutta 2005; Waruingi and Njoroge 2008), many challenges need to be overcome to ensure that these technologies do reach the poor tomorrow. Although nanotechnology is seen as positive by most, overwhelming constraints to investment and governance push some to believe nanotechnologies will probably not be available for the poor (Sparrow 2007).

Though significant contribution has been made by both pure and applied research toward nanotechnologies, currently most of this research has focused on developed countries. Little research has targeted the developing-country needs and in particular the poor. Critical research gaps thus exist in the scientific understanding of ways to improve the situation of the poor (both as producers and as consumers). Most producers have small farm sizes, have low levels of human capital, and consume much of the food they grow. In addition they face a lack of liquidity, low purchasing power, a modest access to agricultural inputs, a low opportunity cost of labor, and limited access to markets. The lack of nanotechnology research tailored to the needs of the poor producers/processors and consumers within developing countries provides an ideal opportunity for the CGIAR to target their efforts at filling these research gaps and therefore to provide an international public good.

There is a wide information gap not only on the potential economic risks associated with nanotech adoption but also on the potential opportunity costs of dismissing technological applications. Because this technology is in its infancy, it is time to try and redirect the research efforts in nanotech toward useful goals for agriculture and sustainable development, taking into account the present and future constraints associated with global warming and bioenergy demand. Public scientists working in this area have kept a relatively narrow focus on certain applications and may not be aware of the needs of agriculture and the consequence of their work.

Prioritization exercises should be conducted in particular sectors in the near future to communicate the needs to the scientific, government, and donor communities. Ex ante assessment of specific technologies could help in this process and help governments to anticipate potential adoption bottlenecks and market risks.

Lastly, more research is needed on governance options, including intellectual property rights and the role of national, regional, and international regulatory frameworks that are bound to be critical for the future use of the technology. The CGIAR could play a significant role in this area and help fill a knowledge gap during the transition between basic research and applied research that results in the development of nanotechnologies that the poor can use in the future for improving agriculture productivity and ensuring food and water safety.

REFERENCES

Anane-Fenin, A. 2008. Nanotechnology in agricultural development in the ACP region. Technical Centre for Agricultural and Rural Cooperation (CTA). <http://knowledge.cta.int/en/Dossiers/S-T-Issues-in-Perspective/Nanotechnology/Articles/Nanotechnology-in-Agricultural-Development-in-the-ACP-Region>. Accessed May 15, 2010.

Argonide. 2005. NanoCeram filters. Argonide Corporation. <http://sbir.nasa.gov/SBIR/successes/ss/9-072text.html>. Accessed May 10, 2010.

Berger, M. 2008. Food nanotechnology: How the industry is blowing it. Nanowerk Spotlight. <http://www.nanowerk.com/spotlight/spotid=5305.php>. Accessed May 20, 2010.

Binder, E. M. 2007. Managing the risk of mycotoxins in modern feed production. *Animal Feed Science and Technology* 133: 149–166.

Bio-Based. 2010. Soy soap research update. < http://www.biobased.us/media/BioBased-2009-Research-Report.pdf >. Accessed May 12, 2010.

Boggan, S. 2006. Once bitten … *The Guardian*. London, United Kingdom. <http://www.guardian.co.uk/science/2008/mar/26/nanotechnology.food>. Accessed May 20, 2010.

Bouwmeester, H., S. Dekkers, M. Noordam, W. Hagens, A. Bulder, C. De Heer, S. ten Voorde, S. Wijnhoven, H. Marvin, and A. Sips. 2007. Health impact of nanotechnologies in food production. Wageningen: RIKILT. <http://edepot.wur.nl/120669>. Accessed May 8, 2010.

________. 2009. Review of health safety aspects of nanotechnologies in food production. *Regulatory Toxicology and Pharmacology* 53: 52–62.

Bowman, D., and G. Gilligan. 2007. How will the regulation of nanotechnology develop? Clues from other sectors. In *New global frontiers in regulation: The age of nanotechnology*, ed. G. Hodge, D. Bowman, and K. Ludlow. Cheltenham, UK: Edward Elgar.

Bowman, D., and G. Hodge. 2009. Counting on codes: An examination of transnational codes as a regulatory governance mechanism for nanotechnologies. *Regulation & Governance* 3 (2): 145–164.

Bozeman, B., J. Hardin, and A. Link. 2008. Barriers to the diffusion of nanotechnology. *Economics of Innovation and New Technology* 17 (7): 749–761.

Bugos, G. 1992. “Intellectual Property Protection in the American Chicken-Breeding Industry.” Business History Review 66 (Spring): 127-168.

Byrne, J. 2010. Food sector and R&D need to chew the nano fat for wider take-up: Analyst. FoodNavigator.com. <http://www.foodnavigator.com/Science-Nutrition/Food-sector-and-R-D-need-to-chew-the-nano-fat-for-wider-take-up-analyst>. Accessed May 18, 2010.

Cairns, C. 2006. Re: Food and Drug Administration-regulated products containing nanotechnology materials. <http://www.consumersunion.org/pub/core_product_safety/004667.html>. Accessed May 10, 2010.

Carter, C. A., and G. P. Gruère. 2003. Mandatory labeling of genetically modified foods: Does it really provide consumer choice? *AgBioForum* 6 (1–2): 68–70.

Chau, C., S. Wu, and G. Yen. 2007. The development of regulations for food nanotechnology. *Trends in Food Science & Technology* 18 (5): 269–280.

Choy J.-H., S.-J. Choi, J.-M. Oh, and T. Park. 2006. Clay minerals and double layered hydroxides for novel biological applications. *Applied Clay Science* 36: 122– 132.

Chun, A. L. 2009. Will the public swallow nanofood? *Nature Nanotechnology* 4 (12): 790–1.

Claassens, C., and M. Motuku. 2006. Nanoscience and nanotechnology research and development in South Africa. *Nanotechnology Law & Business* 3 (2): 217–228.

Clemants, M. 2009. Pullet production gets silver lining. Poultry International, April 2009. <http://www.wattagnet.com/Poultry_International/4166.html>. Accessed May 6, 2010.

Cohen, J., and R. Paarlberg. 2004. Unlocking crop biotechnology in developing countries: A report from the field. *World Development* 32 (9): 1563–1577.

Cope, S., L. Frewer, J. Houghton, G. Rowe, A. Fischer, and J. de Jonge. 2010. Consumer perceptions of best practice in food risk communication and management: Implications for risk analysis policy. *Food Policy* 35 (4): 349–357.

Court, E., S. Daar, E. Martin, T. Acharya, and P. Singer. 2004. Will Prince Charles et al. diminish the opportunities of developing countries in nanotechnology? Nanotechweb.org <http://nanotechweb.org/cws/article/indepth/18909>. Accessed May 6, 2010.

Davies, E. 2010. The taste of tiny: Putting nanofoods on the menu. *The New Scientist* (2761). May.

Department of Science and Technology. 2005. *The national nanotechnology strategy*. Pretoria, South Africa. Publisher Department of S&T. <http://www.dst.gov.za/publications-policies/strategies-reports/reports/Nanotech.pdf>. Note this is a downloaded document, published by the Republic of South Africa.

DeRosa, M. C., C. Monreal, M. Schnitzer, R. Walsh, and Y. Sultan. 2010. Nanotechnology in fertilizers. *Nature Nanotechnology* 5: 91.

Doyle, M. 2006. Nanotechnology: A brief literature review. Food Research Institute Briefings (June). <http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Nanotechnology+:+A+Brief+Literature+Review#0>. Accessed May 5, 2010.

EFSA 2009 Proceeding of Conference on Nanotechnology for a sustainable economy, Prague June 2-5, 2009, pub European Commission <ftp://ftp.cordis.europa.eu/pub/nanotechnology/docs/enf2009_proceedings_en.pdf>.

ETC Group. 2004. Down on the farm: The impact of nano-scale technologies on food and agriculture. Action Group on Erosion, Technology, and Conservation. November, Ottawa, Canada. <www.etcgroup.org>.

________. 2005. *The potential impacts of nano-scale technologies on commodity markets: The implications for commodity dependent developing countries*. Trade-Related Agenda Development and Equity Research Papers. Geneva, Switzerland.

________. 2008. Downsizing development: An introduction to nano-scale technologies and implications for the global south. Developmental Dossier, UNCTAD/NGLS/2008/1. Geneva, Switzerland: UN Non-Governmental Liaison Service.

Evenson, R. 1994. Agricultural Technology Transfer: Concepts, Experience and Issues. In *Agricultural Technology: Policy Issues for the International Community*, edited by J. Anderson. Wallingford: CAB International.

Falck-Zepeda, J., A. Cavialeri, and P. Zambrano. 2009. *Delivering genetically engineered crops to poor farmers: Recommendations for improved biosafety regulations in developing countries*. IFPRI Brief 014. Washington, D.C.: International Food Policy Research Institute.

FAO (Food and Agricultural Organization of the United Nations). 1996. *Rome declaration on world food security*. World Food Summit. November 13–17. Rome.<http://www.fao.org/docrep/003/w3613e/w3613e00.HTM>. Accessed May 20, 2010.

FAO-WHO (World Health Organization). 2009. *FAO/WHO joint expert meeting on the application of nanotechnologies in the food and agriculture sectors: Potential food safety applications*. Meeting Report. Rome.

Federal Institute for Risk Assessment (BfR). 2007. The majority of consumers view the development of nanotechnology favourably. News release. <http://www.bfr.bund.de/cd/10563>. Accessed May 29, 2010.

Fink, C., and K. E. Maskus. 2005. Why we study intellectual property rights and what we have learned? In *Intellectual property rights and development: Lessons from recent economic research*, ed. C. Fink and K. E. Maskus. Washington, D.C.; London: The World Bank and Oxford University Press.

Foladori, G., and N. Invernizzi. 2008. Nanotechnologies in Latin America. Manuscript (p. 128). Berlin, Germany: RLS. <http://www.rosalux.de/fileadmin/rls_uploads/pdfs/Manuskripte_81.pdf>. Accessed May 20, 2010.

Food Safety Authority of Ireland (FSA). 2008. The Relevance for Food Safety of Applications of Nanotechnology in Food and Feed. <http://www.nanowerk.com/nanotechnology/reports/reportpdf/report119.pdf>. Accessed May 29, 2010.

Garber, C. 2006. Nanotechnology food coming to a fridge near you. Nanowerk Spotlight. <http://www.nanowerk.com/spotlight/spotid=1360.php>. Accessed May 20, 2010.

Gardea-Torresdey, J. L., J. G. Parsons, K. Dokken, J. Peralta-Videa, H. E. Troiani, P. Santiago, and M. Jose-Yacaman. 2002.Formation and growth of Au nanoparticles inside live alfalfa plants. *Nano Lett* 2: 397–401.

Gardea-Torresdey, J.L., E. Gomez, J. Peralta-Videa, J. G. Parsons, H. E. Troiani, and M. Jose-Yacaman. 2003. Alfalfa sprouts: A natural source for the synthesis of silver nanoparticles. *Langmuir* 19: 1357–1361.

Gilman, G. P. 2006. A simple device for arsenic removal from drinking water using hydrotalcite. *Science of the Total Environment* 366: 926–931.

GENS (Green Earth Nano Science). 2009. GENS-NANO self sanitizing coating for walls and ceilings. *Canadian Poultry*. <http://www.canadianpoultrymag.com/content/view/1653/67/>. Accessed May 19, 2010.

Gruère, G. P. 2006 a. *An analysis of trade related international regulations of genetically modified food and their effects on developing countries*. Environment and Production Technology Discussion Paper 147. Washington, D.C.: International Food Policy Research Institute.

Gruère, G. P. 2006 b. A preliminary comparison of the retail level effects of genetically modified food labelling policies in Canada and France. *Food Policy* 31 (2): 148–161.

Gruère, G. 2009. *Biosafety decisions and perceived commercial risks: The role of GM-free private standards.* Discussion Paper 00847. Washington, D.C.: International Food Policy Research Institute.

Gruère, G. P., and M. W. Rosegrant. 2008. Assessing the implementation effects of the biosafety protocol's proposed stringent information requirements for genetically modified commodities in countries of the Asia Pacific economic cooperation. *Review of Agricultural Economics* 30(2): 214–232.

Gruère, G., and D. Sengupta. 2009. GM-free private standards and their effects on biosafety decision-making in developing countries. *Food Policy* 34 (5): 399–406.

Harrington, R. 2010. Nano risk assessment a work in progress. FoodNavigator.com. <http://www.foodnavigator.com/Science-Nutrition/Nano-risk-assessment-a-work-in-progress>.

Harrington, R. 2010. Nanotech disclosure may trigger R&D exodus from UK. FoodNavigator.com. <http://www.foodnavigator.com/Legislation/Nanotech-disclosure-may-trigger-R-D-exodus-from-UK>. Accessed May 20, 2010.

Hashim, U., E. Nadia, and S. Salleh. 2009. Nanotechnology development status in Malaysia: Industrialization strategy and practices. *International Journal of Nanotech and Materials* 2 (1): 119–134.

Hayami, Y. and K. Otsuka. 1994. Beyond the Green Revolution: Agricultural Development Strategy into the New Century. In *Agricultural Technology: Policy Issues for the International Community,* edited by J. R. Anderson. Wallingford: CAB International.

He, L., N.-J. Kim, H. Li, Z. Hu, and M. Lin. 2008. Use of a fractal-like gold nanostructure in surface-enhanced Raman spectroscopy for detection of selected food contaminants. *Journal of Agricultural and Food Chemistry* 56: 9843–9847.

Helmus, M. N. 2006. How to commercialize nanotechnology. *Nature Nanotechnology* 1 (3): 157–158.

Helmut Kaiser. 2006. *Study: Nanotechnology in Food and Food Processing Worldwide 2003–2006–2010–2015*. Tubingen, Germany.

Hillie, T., and M. Hlophe. 2007. Nanotechnology and the challenge of clean water. *Nature Nanotechnology* 2: 663–664.

Hillie, T., M. Munasinghe, M. Hlope, and Y. Deraniyagala. 2006. *Nanotechnology, water and development*. Nursing Research. Dillon, CO: Meridian Institute. <http://idl-bnc.idrc.ca/dspace/handle/123456789/32428>. Accessed May 21, 2010.

Hoddinott, J., J. A. Maluccio, J. R. Behrman, R. Flores, and R. Martorell. 2008. Effect of a nutrition intervention during early childhood on economic productivity in Guatemalan adults. *Lancet* 371 (9610): 411–416.

Howells, G. 2009. Product liability for nanotechnology. *Journal of Consumer Policy* 32 (4): 381–391.

Hu, Y., G. Shen, H. Zhu, and G. Jiang. 2010. A class-specific enzyme-linked immunosorbent assay based on magnetic particles for multiresidue organophosphorus pesticides. *Journal of Agricultural and Food Chemistry* 58: 2801–2806.

Jarvis, L. 1986. Livestock Development in Latin America, Washington: The World Bank.

Jarvis, L. 1991. The Role of Markets and Public Intervention in the Chilean Fruit Development Since the 1960's: Some Lessons for Technology Policies. Paper read at Conference on Agricultural Technologies, at Virginia

Joseph, T., and M. Morrison. 2006. *Nanotechnology in agriculture and food*. Woodrow Wilson International Center for Scholars. Project on Emerging Nanotechnologies. <www.nanoforum.org>. Accessed May 20, 2010.

Judd, M.; J. Boyce, and R. Evenson. 1986. Investing in Agricultural Supply: The Determinants of Agricultural Research and Extension Investment. *Economic Development and Cultural Change* Vol. 35 (1).

Kahan, D. M. 2009. Nanotechnology and society: The evolution of risk perceptions. *Nature Nanotechnology* 4 (11): 705–706.

Karn, B., T. Kuiken, and M. Otto. 2009. Nanotechnology and in situ remediation: A review of benefits and potential risks. *Environmental Health Perspectives* 117 (12): 1823–1831.

Kumar, S.R., V. P. I. Ahmed, V. Parameswaran, R. Sudhakaran, V. S. Babu, and A. S. Hameed. 2008. Potential use of chitosan nanoparticles for oral delivery of DNA vaccine in Asian sea bass (*Lates calcarifer*) to protect from *Vibrio* (*Listonella*) *anguillarum*. *Fish & Shellfish Immunology* 25: 47–56.

Kuzma, J. 2010. Nanotechnology in animal production: Upstream assessment of applications. *Livestock Science* 130 (1–3): 14–24.

Kuzma, J., and P. VerHage. 2006. Nanotechnology in agriculture and food production: Anticipated applications. Woodrow Wilson International Center for Scholars. Project on Emerging Nanotechnologies. <http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:NANOTECHNOLOGY+IN+AGRICULTURE+AND+FOOD+PRODUCTION#0>. Accessed May 20, 2010.

Kuzma J, Romanchek J, Kokotovitch A. Upstream Oversight Assessment for Agrifood

Nanotechnology: A Case Studies Approach. *Risk Analysis*. 2008;28(4):1081-98.

Lal, R. 2007. Ushering soil science into the 21 century. President's message, Soil Science Society of America. Nov 7, 2007, Madison Wisconsin.<https://www.soils.org/about-society/presidents-message/archive/16>. Accessed May 22, 2010.

Larkins, B., S. Bringgs, D. Delmer, R. Dick, R. Flavell, and J. Gressel. 2008. *Emerging technologies to benefit farmers in sub-Saharan Africa and South Asia*. Washington, D.C.: National Academies Press.

Liu, L. 2009. *Emerging nanotechnology power nanotechnology R & D and business trends in the Asia Pacific rim*. papers.ssrn.com. London, United Kingdom. <http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1586279>. Accessed May 20, 2010.

Liu G, J Wang, and Y Lin. 2006. "Nanoparticle Labels/ Electrochemical Immunosensor for Detection of Biomarkers." In Nanotech 2006 Technical Proceedings of the 2006 NSTI Nanotechnology Conference and Trade Show, vol. 2, ed. M. Lauden, R. Romanowicz, pp. 192-195. Nano Science & Technology Institute, Cambridge, MA.

Ludlow, K., D. Bowman, and G. Hodge. 2007. Conclusions: Big regulatory questions—something old, something new, something borrowed, something blue? In *New frontiers in regulation: The age of nanotechnology*, ed. G. Hodge, D. Bowman, and K. Ludlow. Cheltenham, UK: Edward Elgar.

Luykx, D. M. A.M., R.J.B. Peters, S. M. van Ruth, and H. Bouwmeester. 2008. A review of analytical methods for the identification and characterization of nano delivery systems in food. *Journal of Agricultural and Food Chemistry* 56: 8231–8247.

Lyndhurst, B. 2009. *An evidence review of public attitudes to emerging food technologies*. Social Science Research Unit, Food Standards Agency (March), 89. <http://www.foodbase.org.uk/admintools/reportdocuments/370-1-647_Emerging_Food_Technologies_Final_Report_with_logo.pdf>. Accessed May 15, 2010.

Lyons, K. 2010. Nanotechnology: Transforming food and the environment. *Food First Backgrounder* 16 (1): 1–4.

MacLurcan, D. C. 2005. Nanotechnology and developing countries Part 1: What possibilities? *AzoNano Online Journal of Nanotechnology* 1 (September): 1–10.

Mai, G. 2008. Nanotechnology could kill small farmers. PIA Press Release. <http://www.pia.gov.ph/?m=12&r=&y=&mo=&fi=p081008.htm&no=02>. Accessed May 20, 2010.

Majid, E., K. B. Male and J. H. T. Luong.2008. *Boron Doped Diamond Biosensor for Detection of Escherichia coli*. J. Agric. Food Chem. 56: 7691 - 7695.

Mansfield, E., J. Rapaport, A. Romeo, E. Villani, S. Wagner, and R. Husic. 1977. *The production and application of new industrial technology*. New York: Norton.

Marchant, G. E., G. A. Cardineau, and T. P. Redick. 2010. *Thwarting consumer choice: The case against mandatory labeling of genetically modified foods*. Washington, D.C.: AEI Press.

Marette, S., J. Roosen, A. Bieberstein, S. Blanchemanche, and F. Vandermoere. 2009. Impact of environmental, societal and health information on consumers' choices for nanofood. *Journal of Agricultural & Food Industrial Organization* 7 (2): 11.

Masters, W. A. 2003. Research prizes: A mechanism to reward agricultural innovation in low-income regions. *AgBioForum* 6: 71–74.

Meridian Institute. 2007. Nanotechnology, commodities & development. Nanotechnology. International Workshop on Nanotechnology, Commodities, and Development Rio de Janeiro, 29 – 31 May 2007 <http://sites.merid.org/nano/commoditiesworkshop/files/Nano_and_Commodities_Overview_Document_070827.pdf>. Accessed June 8, 2010.

Miller, D. D. 2010. Food nanotechnology: New leverage against iron deficiency. *Nature Nanotechnology* 5 (5): 318–319.

Miller, G., and R. Senjen. 2008. *Out of the laboratory and on to our plates: Nanotechnology in food and agriculture*. Friends of the Earth.

Mowery, D., and N. Rosenberg. 1989. *Technology and the pursuit of economic growth*. Cambridge: Cambridge University Press.

Mowery, D. 1992. International Collaborative Ventures and the Commercialization of New Technologies. In *Technology and the Wealth of Nations*, edited by R. L. Nathan Rosenberg, and David Mowery. Stanford: Stanford University Press.

Mukal, D., N. Sexena, and P. D. Dwivedi. 2009. Emerging trends of nanoparticles application in food technology: Safety paradigms. *Nanotoxicology* 3 (10): 10–18.

NanoBio-RAISE. 2007. *Nanotechnology and food*. Delft, The Netherlands. <http://files.nanobio-raise.org/Downloads/Nanotechnology-and-Food-fullweb.pdf>. Accessed May 20, 2010.

National Nanotechnology Coordinating Office 2009. Nanotechnology-enabled sensing. Report of the National Nanotechnology Initiative Workshop, May 5 - 7, 2009. 42 pg. <http://www.nano.gov/NNI-Nanosensors-stdres.pdf>. Accessed May 20, 2010.

Narrod, C., D. Roy, A. Gulati, N. Minot, and C. Delgado. 2007. Food safety research priorities for the CGIAR: A concept note from IFPRI for the Science Council.

Narrod, C. and K. Fuglie. 2000. “Private-Sector Investment in Livestock Breeding. ” *Agribusiness: An International Journal*, 4 (6), 2000, pp. 457-470.

Narrod, C. L. Unnevehr and C. Pray. April 2000. "Food Safety Research: What is the Division of Public and Private Effort?" Unpublished Working paper.

Narrod et al. 2007. Role of the CGIAR in Food Safety Research in "Food Safety in the CGIAR IFPRI-CGIAR Science Council Roundtable on Food Safety Report and Recommendations arising from a joint IFPRI Science Council sponsored Roundtable on possible Approaches to Food Safety Research in the CGIAR, H. Okusu, C. Narrod, and D. Roy 2007. Rome. Italy. <ftp://ftp.fao.org/docrep/fao/010/a1631e/a1631e00.pdf >

Nature Nanotechnology. 2007. Tackling global poverty. *Nature Nanotechnology* 2 (11): 661.

Nemets, A. 2004. China's nanotech revolution. *China Brief* 4 (16). <http://www.jamestown.org/single/?no_cache=1&tx_ttnews[swords]=8fd5893941d69d0be3f378576261ae3e&tx_ttnews[any_of_the_words]=nanotech&tx_ttnews[tt_news]=26719&tx_ttnews[backPid]=7&cHash=0e2e4df976>. Accessed May 20, 2010.

New Scientist. 2010. *How to persuade us to swallow nanofood*. London: The New Scientist.

Ngayta, K. 2009. Nanotechnology: How prepared is Uganda? *Daily Monitor*. Kampala, Uganda. <http://www.monitor.co.ug/Business/Technology/-/688612/711106/-/tc0enq/-/index.html>. Accessed May 20, 2010.

Niosi, J., and S. Reid. 2007. Biotechnology and nanotechnology: Science-based enabling technologies as windows of opportunity for LDCs? *World Development* 35 (3): 426–438.

NNI (National Nanotechnology Initiative). 2007. *National nanotechnology initiative strategic plan*. <http://www.nano.org>. Accessed May 20, 2010.

________. 2009. *Nanotechnology-enabled sensing*. Report of the National Nanotechnology Initiative Workshop. Arlington, VA. May 5–7, 2009. <http://www.nano.org>. Accessed May 20, 2010.

Nord, E. 2009. Top 10 reasons for using nanotech in food. Discovery. com. <http://news.discovery.com/tech/ten-reasons-nano-food.html>. Accessed May 20, 2010.

NRC (National Research Council). 2008. *Emerging technologies to benefit farmers in sub-Saharan Africa and South Asia.* Washington, D.C.: National Academies Press.

Nuffield Council on Bioethics. 2004. *The use of genetically modified crops in developing countries.* Discussion Paper. London.

Observatory NANO. 2010. *Nanotechnologies for nutrient and biocide delivery in agricultural production*. Working Paper Version. April 2010. <http://www.observatorynano.eu>. Accessed May 20, 2010.

Ochoa, J., J. M. Irache, I. Tamayoa, A. Walz, V. G. DelVecchio, and C. Gamazoa. 2007. Protective immunity of biodegradable nanoparticle-based vaccine against an experimental challenge with *Salmonella Enteritidis* in mice. *Vaccine* 25 (2007): 4410–4419.

OECD (Organization for Economic Cooperation and Development). 2010. *Report of the questionnaire on regulatory regimes for manufactred nanomaterials*. Environment. Paris.

OECD and Allianz. 2008. *Sizes that matter: Opportunities and risks of nanotechnologies*. Report in cooperation with the OECD International Futures Programme. <http://www.oecd.org/dataoecd/32/1/44108334.pdf>. Accessed May 20, 2010.

Organic and Non-GMO Report. 2010. Canada joins ban in nano in organics. June 7, 2010. <http://www.nanotech-now.com/news.cgi?story_id=38555>. Accessed June 10, 2010.

Paarlberg, R. 2009. *Starved for science: How biotechnology is being kept out of Africa*. Cambridge, MA: Harvard University Press.

Paull, J., and Lyons, K. 2008. Nano-in-food: Threat or opportunity for organic food? In *Cultivate the Future.* Proceedings from the Nanotechnology Workshop at the16th IFOAM World Organic Congress, June 16–20, 2008, in Modena, Italy. International Federation of Organic Agriculture Movements (IFOAM).

Portney, P. 1990. *Public policies for environmental protection*. Washington, D.C.: Resources for the Future.

Pray, C., and R. Echeverría. 1991. Private-sector research in less-developed countries. In *Agricultural research policy: International quantitative perspective*, ed. P. Pardey, J. Roseboom, and J. Anderson. Cambridge: Cambridge University Press.

Pray, C., and K. Fuglie. 2001. *Private Investment in Agricultural Research and International Technology Transfer in Asia*. Agricultural Economics Report 805, Economic Research Service, U.S. Department of Agriculture, Washington, DC, Nov.

President's Council of Advisors on Science and Technology. 2010. *Report to the president and Congress on the third assessment of the National Nanotechnology Initiative*. Washington, D.C.

Redick, T. P. 2007. The Cartagena protocol on biosafety: Precautionary priority in biotech crop approvals and containment of commodities shipments. *Colorado Journal of International Environmental Law and Policy* 18: 51–116.

Romig, A., A. Baker, J. Johannes, T. Zipperian, K. Eijkel, B. Kirchhoff, H. Mani, C. Rao, and S. Walsh. 2007. An introduction to nanotechnology policy: Opportunities and constraints for emerging and established economies. *Technological Forecasting and Social Change* 74 (9): 1634–1642.

Rosenberg. 1990. Why Do Firms Do Basic Research With Their Own Money? *Research Policy* 19:2:165-174.

Royal Society/Royal Academy of Engineering (RS-RAE). 2004. *Nanoscience and nanotechnologies: Opportunities and uncertainties*. London: RS-RAE.

Salamanca-Buentello, F., D. L. Persad, E. B. Court, D. K. Martin, A. S. Daar, and P. A. Singer. 2005. Nanotechnology and the developing world. *PLoS Medicine* 2 (5): 383–386, e97.

Sanderson, K. 2009. Tighter nanotech regulations touted. *Nature* 457 (7230): 647.

Sandoval, B. 2009. Perspectives on FDA's regulation of nanotechnology: Emerging challenges and potential solutions. *Comprehensive Reviews in Food Science and Food Safety* 8 (4): 375–393.

Satterfield, T., M. Kandlikar, C. E. Beaudrie, J. Conti, and B. Herr Harthorn. 2009. Anticipating the perceived risk of nanotechnologies. *Nature Nanotechnology* 4 (11): 752–758.

Schneider, A. 2010. Obsession with nanotech growth stymies regulators. AOL News. <http://www.aolnews.com/nation/article/obsession-with-nanotechnology-growth-stymies-regulators/19401712>. Accessed May 18, 2010.

Schneider, A. 2010. Regulated or not, nano-foods coming to a store near you. AOL News. <http://www.aolnews.com/nanotech/article/regulated-or-not-nano-foods-coming-to-a-store-near-you/19401246>. Accessed May 18, 2010.

Science and Technology Committee of the House of Lords. 2010. *Nanotechnologies and food*. Published by the Authority of the House of Lords, London : The Stationery Office Limited. <http://www.publications.parliament.uk/pa/ld200910/ldselect/ldsctech/22/22i.pdf>. Accessed May 20, 2010.

Scott, N. R. 2005. Nanotechnology and animal health. *Rev. sci. tech. Off. int. Epiz*. 24 (1): 425–432.

Scott, N. R. 2007. Nanoscience in veterinary medicine. *Veterinary Research Communications* 31(Suppl. 1): 139–144.

Scott, N., and H. Chen. 2003. Nanoscale science and engineering for agriculture and food systems. Washington, D.C.: Cooperative State Research, Education and Extension Service, United States Department of Agriculture, (September 2003). <http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:NANOSCALE+SCIENCE+AND+ENGINEERING+FOR+AGRICULTURE+AND+FOOD+SYSTEMS#0>. Accessed May 20, 2010.

Scrinis, G., and K. Lyons. 2007. The emerging nano-corporate paradigm: Nanotechnology and the transformation of nature, food and agri-food systems. *International Journal of Sociology of Food and Agriculture* 15 (2): ISSN 0798–1759.

Secretariat of the Convention on Biodiversity. 2000. Cartagena protocol on biosafety to the Convention on Biodiversity. Montreal, Canada. <http://www.cbd.int/doc/legal/cartagena-protocol-en.pdf>. Accessed May 23, 2010.

Shelke, K. 2006. Tiny, invisible ingredients. FoodProcessing.com. <http://www.foodprocessing.com/articles/2006/227.html>. Accessed May 20, 2010.

Shi, Y. H., Z. R. Xu, J. L. Feng, and C. Z. Wang. 2006. Efficacy of modified montmorillonite nanocomposite to reduce the toxicity of aflatoxin in broiler chicks. *Animal Feed Science and Technology* 129: 138–148.

Siegrist, M., N. Stampfli, and H. Kastenholz. 2009. Acceptance of nanotechnology foods: A conjoint study examining consumers' willingness to buy. *British Food Journal* 111 (7): 660–668.

Sparrow, R. 2007. Negotiating the nanodivides. In *New global frontiers in regulation: The age of nanotechnology*, ed. G. Hodge, D. Bowman, and K. Ludlow. Cheltenham, UK: Edward Elgar.

Spielman, D. J., J. I. Cohen, and P. Zambrano. 2006. Policy, investment, and partnerships for agricultural biotechnology research in Africa : Emerging evidence. *African Technology Development Forum Journal* 3 (4): 3–11.

Spielman, D. J., and R. Pandya-Lorch. 2009. *Millions fed: Proven successes in agricultural development*. Washington, D.C.: International Food Policy Research Institute.

Spriull, J. C. 2006. Novel pre-harvest approaches to control enteric food-borne bacteria in poultry. M.S. thesis, North Carolina State University, Raleigh.

Sreelata, M. 2008. India looks to nanotechnology to boost agriculture. Sci-Dev.net. <http://www.scidev.net/en/news/india-looks-to-nanotechnology-to-boost-agriculture.html>. Accessed May 18, 2010.

Sunding, D., and D. Zilberman. 2001. The agricultural innovation process: Research and technology adoption in a changing agricultural sector. In *Handbook of agricultural economics, volume 1*, ed. B. L. Gardner and G. C. Rausser. Amsterdam, The Netherlands: Elsevier B.V.

Sylvester, D. J., K. W. Abbott, and G. E. Marchant. 2009. Not again! Public perception, regulation, and nanotechnology. *Regulation and Governance* 3 (2): 165–185.

Taylor, M. 2008. *Assuring the safety of nanomaterials in food packaging: The regulatory process and key issues*. Production, (July). Woodrow Wilson International Center for Scholars. <http://eprints.internano.org/62/1/Food_Packaging_pen12.pdf >. Accessed May 20, 2010.

Umali, D., G. Feder, and C. de Haan. 1992. *The balance between public and private sector activities in the delivery of livestock services.* Washington, D.C.: World Bank.

USDA (United States Department of Agriculture), Cooperative State Research and Extension Service. 2003. *Nanoscale science and engineering for agriculture and food systems*. National Planning Workshop, Nov. 18–19, 2002. Report submitted to the Cooperative State Research and Extension Service. Washington , D.C.

UN 2006 Emerging Challenges, Nanotechnology and the Environment <http://www.unep.org/yearbook/2007/PDF/7_Emerging_Challenges72dpi.pdf>. Accessed May 19, 2010.

Walsh, S., and T. Medley. 2008. A framework for responsible nanotechnology. In *The yearbook of nanotechnology in society, volume I: Presenting futures*, ed. E. Fisher, C. Selin, and J. Widemore. New York: Springer.

Wang, M. and Z. Li 2008 *Nano-composite* ZrO_2*/Au film electrode for voltammetric detection of parathion.* Sensors and Actuators B: Chemical 133(2): 607-612.

Warad, H., and J. Dutta. 2005. Nanotechnology for agriculture and food systems: A view. In proceedings of *The Second International Conference on Innovations in Food Processing Technology and Engineering*, Bangkok (p. 11–13). <http://www.nano.ait.asia/Download/AIT Papers/2005/Nanotechnology For Agriculture And Food Systems _ A View.pdf>. Accessed May 20, 2010.

Waruingi, M., and J. Njoroge. 2008. Nanotech in Kenya. *Business Daily Africa*. <http://biokatalis.net/?p=16>. Accessed May 21, 2010.

Watson, E. 2010. Unilever: Nano labels must be 'meaningful and specific'. FoodNavigator.com. <http://www.foodnavigator.com/Product-Categories/Food-safety-and-labelling/Unilever-nano-labels-must-be-meaningful-and-specific>. Accessed May 20, 2010.

World Bank. 2008. *World development report 2008: Agriculture for development*. Washington, D.C.

World Health Organization. 2008. *Safer water, better health: Costs, benefits and sustainability of interventions to protect and promote health*. Geneva.

United Nations, (2008). Downsizing Development: An introduction to nano-scale technologies and implications for the global south by ETC, Inc. Developmental Dossier, Non-Governmental Liaison Service. UNCTAD/NGLS/2008/1, Geneva, Switzerland, 98 p.

United States Department of Agriculture,. (2003). *Nanoscale science and engineering for agriculture and food systems*. National Planning Workshop, Nov. 18 – 19, 2002. A Report submitted to the Cooperative State Research and Extension Service. Washington , DC. 68 p.

Yada, R. 2009. Nanotechnology: A new frontier in foods, food packaging, and nutrient delivery. In *Nanotechnology in food products*, ed. L. Pray and A. Yaktine. Washington, D.C.: National Academies Press.

Yavuz, C. T., J. T. Mayo, W.W. Yu, A. Prakash, J. C. Falkner, S. Yean, L. Cong, H. J. Shipley, A. Kan, M. Tomson, D. Natelson, and V. L. Colvin. 2006. Low-field magnetic separation of monodisperse Fe3O4 nanocrystals. *Science* 314: 964–967.

Ying-hua, S., X. Zi-rong, F. Jian-lei, H. Cai-hong, X. Mia-sheng. In vitro adsorption of Aflatoxin Adsorbing Nano-additive for Aflatoxin B_1, B_2, G_1, G_2. Scientia Agricultura Sinica. DOI: CNKI:SUN:ZNYK.0.2005-05-031 2005.

Zentner, R., and W. Peterson. 1984. An economic evaluation of public wheat research and extension expenditures in Canada. *Canadian Journal of Agricultural Economics* 32: 327–353.

Zilberman, D., and M. Marra. 1993. Agricultural externalities. In *Agricultural and environmental resource economics*, ed. G.A. Carlson, *D. Zilberman*, and J. Miranowski. New York: Oxford University Press.

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